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Targeted management of agricultural nitrogen for tackling air pollution in the Indo-Gangetic Plain and Himalayan Foothill region

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Authors

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Contents

List of abbreviations

4R	Right Source at the Right Rate, Right Time and Right Place
CAQM	Commission for Air Quality Management
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CPCB	Central Pollution Control Board
CBG	Compressed Biogas
EEFs	enhanced efficiency fertilisers
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies
GAPO	Green Ammonia Procurement Obligation
IGP-HF	Indo-Gangetic Plain–Himalayan Foothills
AE	agronomic efficiency
AEOs	agricultural extension officers
AKCs	Agriculture Knowledge Centres
BARI	Bangladesh Agricultural Research Institute
DAE	Department of Agricultural Extension
GHG	greenhouse gas
KVK	Krishi Vigyan Kendra
MoEFCC	Ministry of Environment, Forest and Climate Change
MRV	Monitoring, Reporting & Verification
NBPT	N-(n-butyl) thiophosphoric triamide (Urease Inhibitor)
NCAP	National Clean Air Programme
NCU	neem coated urea
NH_3	ammonia
ACZs	agro-climatic zones
NNA	National Nitrogen Authority
NPK	Nitrogen (N), Phosphorus (P), and Potassium (K)
NO_x	nitrogen oxides
NUE	nitrogen use efficiency
LCS	low-cost sensors
LMT	lakh metric tonnes
PFP	partial factor productivity
FPOs	Farmer Producer Organisations
FUE	fertiliser use efficiency
PM2.5	fine particulate matter
PM-PRANAM	PM Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth
ICIMOD	International Centre for Integrated Mountain Development
PNMPs	precision nutrient management practices
JTAs	junior technical assistants
PAU	Punjab Agricultural University
SO_2	sulphur dioxide
SAAOs	Sub-Assistant Agriculture Officers
SAUs	state agricultural universities
SOPs	standard operating procedures
UPCAMP	Uttar Pradesh Clean Air Management Project
USGs	urea super granules

Executive summary

Agricultural ammonia (NH_3) has emerged as one of the most critical yet under-regulated contributors to fine particulate matter ($PM_{2.5}$) pollution across the Indo-Gangetic Plain and Himalayan Foothill (IGP-HF) region. While countries in this region have made notable progress in reducing combustion-related emissions such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x), ammonia emissions from fertiliser use have remained largely unchecked. As a result, ammonia now plays a central role in regional air pollution. Across the IGP-HF, spanning across parts of India, Pakistan, Nepal, and Bangladesh, secondary particulate matter formed through atmospheric reactions involving ammonia constitutes a substantial proportion of wintertime $PM_{2.5}$.

Historically, air pollution control strategies have focused on visible and easily regulated sources, including vehicle tailpipe emissions, industrial factories, power plants, and crop residue burning. In contrast, ammonia emissions from agricultural fertilisers have largely escaped policy attention, despite their significant contribution to winter smog and chronic air quality degradation. This policy blind spot has effectively rendered agricultural ammonia an "invisible" contributor of poor air quality in the IGP-HF region. Excessive and imbalanced fertiliser use, particularly urea, has degraded soil health, reduced nitrogen use efficiency (NUE), and created ammonia emission hotspots detectable through satellite observations.

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model demonstrates that fertiliser-related ammonia emissions contribute approximately 3.5–6.0 micrograms per cubic meter (µg/m^3) to the annual $PM_{2.5}$ burden, with seasonal peaks of 7.0–7.6 µg/m^3 during intensive agricultural periods. These emissions are inherently transboundary, and deteriorate air quality well beyond their points of origin, underscoring the need for coordinated regional policy action. This report highlights a gap in current air pollution control efforts.

Over the past decade, policy and legal interventions have focused predominantly on crop residue burning (CRB). Investments in stubble management technologies and enforcement mechanisms are beginning to show results, and $PM_{2.5}$ emissions from crop fires are projected to decline by 2035. However, during the same time, pollution linked with fertiliser use has been increasing. As emissions from combustion sources declines, ammonia-driven particulate pollution is becoming increasingly dominant, yet it remains largely unaddressed in air quality planning.

Low NUE therefore represents a critical missing link in clean air policy and implementation. Consequently, the region encounters a challenge in attaining $PM_{2.5}$ concentrations to 35 µg/m^3 by 2035 ("35-by-35" goal), by targeting combustion-related sources alone. Ammonia emissions from urea do not remain confined to agricultural fields; they disperse into towns and cities, where they react with other atmospheric pollutants to form secondary $PM_{2.5}$, a major contributor to winter pollution episodes. At the same time, more than half of the nitrogen applied by farmers is lost to the air or water, resulting in inefficient use of public subsidies, continued soil degradation, and additional environmental harm.

Despite the scale of this challenge, current air quality strategies, such as the National Clean Air Programme (NCAP), remain overwhelmingly city-centric, leaving agricultural ammonia largely outside their operational and regulatory scope. This disconnect has created a significant policy vacuum: the primary sources of NH_3

emissions are in rural districts, while the most severe health impacts are borne by densely populated urban centres that lack jurisdiction over agricultural practices.

The launch of the Prime Minister's Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth (PM-PRANAM) scheme in 2023 marks a major structural shift in India's fertiliser governance. For the first time, states are financially incentivised to reduce the use of chemical fertilisers. The Uttar Pradesh Clean Air Management Project (UPCAMP) provides an early planning of how NUE incentives can be integrated into state-level clean air strategies. Through the adoption of precision nutrient management practices (PNMPs), 4R nutrient stewardship[1], and a robust Monitoring, Reporting, And Verification (MRV) framework, UPCAMP demonstrates a viable pathway for aligning agricultural reform with air quality objectives.

Several countries including Germany, other European Union (EU) member states, and China, have successfully reduced agricultural ammonia emissions through integrated nitrogen governance frameworks and enforceable regulatory caps. Key measures have included improved fertiliser application practices (such as the use of urease inhibitors, soil incorporation, and band application), wider adoption of enhanced efficiency fertilisers and strengthened manure and waste management systems.

Drawing on these international experiences, this report identifies critical policy gaps in the current nitrogen management framework, viewed through an air quality management lens, across the IGP-HF region. It proposes a comprehensive pathway for reform centred on five key opportunities: integrating fertiliser policy with clean air objectives; expanding the use of urease inhibitors through the proposed *Neem Plus* strategy; restructuring fertiliser subsidies to incentivise efficiency rather than volume; adopting an airshed-based, regional governance approach; and establishing a national authority to coordinate nitrogen management across the full value chain, from production and application to emissions and environmental impacts.

When implemented cohesively, these reforms have the potential to reduce ammonia emissions by 30%–40% and substantially lower $PM_{2.5}$ concentrations across the region. In addition to air quality benefits, they can ease fiscal pressures on fertiliser subsidies, improve soil health, and accelerate progress towardss the "35-by–35" regional clean air goal for the IGP-HF region.

The main objective of this report is to position NUE as a critical yet overlooked air quality intervention. While substantial efforts have been undertaken to curb emissions from crop residue burning, fertiliser-related ammonia emissions, an equally potent and rapidly growing source of $PM_{2.5}$, has received far less policy attention. As emissions from combustion sources continue to decline, ammonia-driven secondary $PM_{2.5}$ is becoming increasingly dominant, underscoring that clean air targets in the IGP-HF region cannot be achieved without addressing fertiliser emissions alongside combustion-related sources.

This report proposes a coordinated policy pathway to address rising ammonia emissions and secondary $PM_{2.5}$ formation across the IGP-HF region. To achieve the "35-by-35" goal, the following structural interventions are recommended:

- **Implementing region-specific "package of practices" (PoP) pilots**: Moving beyond uniform national guidelines by launching zonal development pilots (modelled on a 48,000-hectare framework) to design, test and calibrate fertiliser practices tailored to distinct agro-climatic zones across the IGP-HF region.
- **Adopting a cluster-based delivery approach**: Leveraging local technical institutions, specifically Krishi Vigyan Kendras (KVKs), anchored by Farmer Producer Organisations (FPOs), to enable decentralised implementation, effective technology transfer, and sustained capacity building at the farm level.
- **Enabling technological transition to "Neem Plus" fertilisers**: Harmonising regional fertiliser standards to mandate the adoption of Neem Plus, urea coated with advanced urease inhibitors such as NBPT, which can reduce ammonia volatilisation by up to 70% without requiring major behavioural changes from farmers.
- **Restructuring incentives through PM-PRANAM**: Operationalising a "Green Benefit Transfer" mechanism by deploying untied PM-PRANAM grants to provide direct cash incentives (for example, ₹5,000 per hectare) to farmers. This approach bridges the gap between state-level fiscal savings and individual farmer's risk in adopting improved nutrient management practices.
- **Closing the rural monitoring gap**: Establishing a Rural Air Quality Monitoring Network by deploying low-cost sensors alongside reference-grade monitors in intensive agriculture districts, in order to capture systematic identification of ammonia emission hotspots that are currently missed by urban-centric monitoring systems.
- **Institutionalising airshed-based governance**: Establishing National Nitrogen Authority (NNA) to coordinate action across agriculture, fertiliser and environment ministries, and operationalise an Indo-Gangetic Airshed Cooperation Framework to manage transboundary ammonia transport and secondary $PM_{2.5}$ formation.
- **Decoupling agricultural growth from nitrogen consumption**: Aligning long-term agricultural policy with the strategic goal of increasing crop yields while capping total nitrogen consumption, to ensure sustainable food security without further escalating environmental and air quality impacts.

Together, these reforms can provide a practical and regionally coordinated pathway to reduce ammonia emissions, improve air quality, lower fiscal burdens, and strengthen sustainable nitrogen management across the IGP–HF region.

[1] 4R Nutrient Stewardship is a science-based framework for fertiliser management, maximizing crop uptake while minimizing environmental impact. It focuses on applying the right source (proper, balanced fertiliser types) at the right rate (matching nutrient needs), right time (synchronizing with crop uptake), and right place (positioning in the soil). (https://www.sciencedirect.com/science/article/pii/S1877705814011229)

CHAPTER I

Introduction

Air pollution has emerged as one of the most severe environmental and public health challenges in the IGP-HF region, which consistently records some of the highest concentrations of fine particulate matter ($PM_{2.5}$) in the world (World Bank, 2025). While policy and research attention has traditionally focused on emissions from transport, industry, and biomass burning, a growing body of scientific evidence demonstrates that agricultural ammonia (NH_3) is a major yet under-addressed contributor to $PM_{2.5}$ formation across the region (SANH, 2024; Pozzer et al., 2019). In the atmosphere, ammonia reacts with acidic precursors such as sulphur dioxide (SO_2) and nitrogen oxides (NO_x) to form ammonium sulphate and ammonium nitrate, key components of secondary particulate matter responsible for recurring winter smog episodes in northern India (Wang et al., 2025).

Nitrogen-based chemical fertilisers, particularly urea, are extensively used across the IGP-HF to sustain high agricultural productivity. While these inputs have supported yield growth, their excessive and imbalanced application has resulted in large nitrogen surpluses, declining nitrogen use efficiency (NUE), and progressive soil degradation (Elsayed et al., 2025). These inefficiencies have led to the formation of ammonia emission hotspots, now clearly detectable through satellite observations and atmospheric modelling, particularly over intensively cultivated areas of the IGP-HF region (Pawar et al., 2021).

Once emitted, ammonia is readily transported across districts, states, and national boundaries, worsening air quality far beyond its points of origin and underscoring its transboundary nature (World Bank, 2024). Despite the growing scientific consensus regarding the contribution of agricultural ammonia emissions in deteriorating air quality, agricultural ammonia remains largely absent from mainstream air-quality governance in the IGP-HF countries. India's National Clean Air Programme (NCAP), along with city-level Clean Air Action Plans (CAAPs), overwhelmingly prioritise urban emission sources. However, the dominant sources of ammonia lie in rural agricultural landscapes, creating a structural mismatch between jurisdiction, regulatory authority, and health impacts (MoEFCC, 2019). As a result, cities suffering the highest $PM_{2.5}$ exposure lack the institutional reach to manage ammonia emissions emanating from surrounding agricultural districts.

The PM-PRANAM scheme introduced in India in 2023, represents a pivotal opportunity to address this structural gap. By financially incentivising the states to reduce the use of chemical fertilisers and adopt more sustainable nutrient management practices, PM-PRANAM establishes a direct link between agricultural reform and air quality improvement. Complementary initiatives, such as the Uttar Pradesh Clean Air Management Project (UPCAMP), further demonstrate how state-level institutions can integrate precision nutrient management (PNM), enhanced efficiency fertilisers (EEFs), and robust Monitoring, Reporting, and Verification (MRV) frameworks into broader clean-air strategies.

International experience provides strong evidence that agricultural ammonia emissions can be effectively reduced through integrated nitrogen governance. Countries such as Germany (under National Emission Ceilings Directive (NEC), Düngeverordnung or Fertiliser Ordinance (DüV), and Technische Anleitung zur Reinhaltung der Luft or Technical Instructions on Air Quality Control (TA Luft regulations)), several

European Union (EU) member states, and China have implemented regulatory caps and enforceable standards to control ammonia emissions (Hu et al., 2025).

Key measures include mandatory fertiliser application standards, such as soil incorporation of urea, use of urease inhibitors, and band application of manure and/or slurry, as well as low emission manure management, enhanced efficiency fertilisers, and improved waste handling systems (Giannakis et al., 2019; Luo et al., 2025). These experiences offer valuable lessons for South Asian countries seeking to transition towardss a more balanced, efficient, and environmentally sustainable nitrogen economy.

This report synthesises current scientific evidence, identifies key policy gaps, and highlights emerging opportunities to address agricultural ammonia emissions across the IGP-HF region. It presents a coherent framework for integrating fertiliser use efficiency, air-quality governance, and fiscal reforms. The analysis illustrates how targeted agricultural reforms, combined with a shift towardss regional, airshed-based management, can significantly reduce secondary $PM_{2.5}$ concentrations, enhance soil health, and advance India's long-term clean air and sustainability objectives.

Over the past decade, air pollution policy in the IGP-HF region has placed strong emphasis on controlling emissions from crop residue burning, supported by regulatory action, financial incentives, and expanded monitoring systems. These efforts are beginning to deliver results, with emissions from open burning expected to decline in the coming years.

In contrast, fertiliser-related ammonia emissions, an equally potent and increasingly dominant source of secondary $PM_{2.5}$, have received far less policy attention. As combustion-related emissions continue to fall, the relative contribution of ammonia to winter $PM_{2.5}$ is rising, making fertiliser use efficiency (FUE) a critical and unavoidable component of effective air-quality management. This imbalance underscores the central argument of the current report: that FUE must be recognised not merely as an agricultural efficiency indicator, but as a core air pollution control strategy essential for achieving sustained clean air outcomes in the IGP-HF region.

CHAPTER II

Objectives of the study

This study aims to:

1. Quantify the contribution of fertiliser-driven ammonia emissions to secondary $PM_{2.5}$ formation across the IGP-HF region, drawing on peer-reviewed literature, GAINS model output, and satellite-based observations.
2. Identify policy and governance gaps related to ammonia management within existing agricultural and air quality framework across countries in the IGP-HF region.
3. Review and assess global best practices in nitrogen governance and evaluate their applicability and relevance to the IGP-HF context.
4. Analyse emerging policy opportunities, including government incentive schemes and the deployment of enhanced efficiency fertilisers, for reducing agricultural ammonia emissions.
5. Propose a policy roadmap outlining short, medium, and long-term interventions that integrate fertiliser use efficiency, airshed-based governance, fiscal reforms, and institutional restructuring for effective management of fertiliser-related emissions.

CHAPTER III

Methods and Methodology

The study adopts a mixed-method, evidence-integrated approach to assess fertiliser-driven $PM_{2.5}$ emissions and inform nitrogen governance strategies in the IGP-HF region. It begins with a comprehensive review of peer-reviewed literature on ammonia emissions, nitrogen-use efficiency, and secondary $PM_{2.5}$ formation, complemented by an analysis of national and international policy documents, including India's National Clean Air Programme (NCAP), EU's nitrogen directives, and China's nitrogen ceilings policies (MoEFCC, 2019; Wang et al., 2023; EEA, 2025). Secondary data from multilateral institutions and government agencies were also examined to provide broader contextual and policy-relevant insights.

Quantitative data analysis draws on International Institute of Systems Analysis's (IIASA) Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model outputs to estimate $PM_{2.5}$ source contributions across the region, including state-level comparisons of fertiliser-related emissions for the baseline year 2021 and projections for 2035 (Amann et al., 2020). A comparative policy assessment was conducted through cross-country evaluation of nitrogen governance frameworks in the European Union (EU), Germany, Denmark, China, and the Netherlands, with particular attention to their applicability to Ind0-Gangetic agro-ecological conditions and institutional capacities.

In addition, the study also analysed the draft Uttar Pradesh Clean Air Management Project (UPCAMP) and the PM-PRANAM scheme implemented during FY 2023-24, for India. It focuses on the precision nutrient management pilots, Monitoring, Reporting, and Verification (MRV) systems, and projected emission reductions for the former; and fertiliser reductions, fiscal savings and state-level performances for the latter.

Finally, the study synthesises agronomic, environmental, and policy-evidence to propose a short- and long-term roadmap for nitrogen governance and airshed-based interventions, tailored to the IGP–HF region.

CHAPTER IV

Nitrogen overuse and impacts on air quality

Agricultural nitrogen use has expanded rapidly over the past five decades, driven by fertiliser subsidies, technological innovations during the Green Revolution[2], and the intensification of cereal-based cropping systems. While these transformations have substantially enhanced food security, they have also created systemic nitrogen imbalances with far-reaching environmental and atmospheric consequences. Excessive and inefficient use of synthetic fertilisers, particularly urea, has led to declining soil fertility, nutrient runoff, groundwater contamination, and large-scale NH_3 volatilisation, now recognised as a major precursor of secondary $PM_{2.5}$ in the IGP-HF region (Ramalingappa et al., 2023; SANH, 2024).

4.1 Fertiliser subsidies and nitrogen overuse

Long-standing fertiliser subsidy regimes are at the core of excessive nitrogen application in the region. Urea has remained heavily subsidised for decades, with its retail price barely changing despite rising production and import costs. In contrast, phosphatic and potassic fertilisers are governed by the nutrient based subsidy (NBS) framework, where prices fluctuate with global markets (CACP, 2023; DoF, 2023). This dual pricing distorts incentives, encouraging farmers to overuse nitrogen relative to phosphorus or potassium, skewing the recommended N:P: K balance.

As shown in Table 1, Indian states such as Punjab and Haryana, once in the forefront of the Green Revolution in India, now record NPK application ratios more than double the recommended levels. In contrast, in IGP countries such as Bangladesh, Nepal and Pakistan, national guidelines for NPK ratio are lacking, leading to widespread nitrogen overuse. Even when crop yields have plateaued, farmers frequently overapply urea in the misconception that “more nitrogen equals more yield,” notwithstanding the diminishing returns of excess urea application, well-documented in agronomic studies (Govindasamy et al., 2023). The imbalance in NPK application across the IGP-HF region is driven by systemic nitrogen overuse, with significant fractions of applied urea remaining unused by crops and escaping into the environment

4.2 The ecological cost: declining nitrogen use efficiency

Declining nitrogen use efficiency (NUE) has emerged as a critical indicator of the nitrogen imbalance in the IGP-HF region. Field studies show wide variability in NUE across cereal systems, with more than half of applied nitrogen often unabsorbed by crops (Bhatia et al., 2023; FAO, 2025). Poor NUE results not only from overapplication, but also from practices such as surface broadcasting, untimely application, limited soil diagnostics, and the absence of precision nutrient management. Nitrogen losses occur through leaching, runoff, denitrification, and most critically for air quality, ammonia volatilisation. Factors such as alkaline soils, high temperatures, and lack of fertilizer incorporation into the soil, exacerbate atmospheric NH_3 release, and escalate atmospheric nitrogen loading (Anas et al., 2020; Pan et al., 2016).

[2] The Green Revolution (1960s–70s) in India introduced high-yield seeds, modern irrigation, fertilisers, and machinery, greatly increasing food production, especially wheat and rice. It made India self-sufficient in food grains but caused environmental damage and regional inequalities.

TABLE 1 REPORTED NPK RATIOS IN KEY INDIAN STATES AND IGP-HF COUNTRIES

S. No.	Country/State	Recommended NPK Ratio	Approx. Current NPK Ratio	References
	India			
1.1	Punjab	4:2:1	11:5:1	Chand & Pavithra, 2015; FAI, 2022
1.2	Haryana	4:2:1	10:5:1	Chand & Pavithra, 2015; FAI, 2022
1.3	Uttar Pradesh	4:2:1	9:4:1	FAI, 2022
1.4	Bihar	4:2:1	11.6: 3.5: 1	FAI, 2022
1.5	West Bengal	4:2:1	7:3:1	FAI, 2022
	Nepal	No national guideline	Nitrogen skewed: High nitrogen, low phosphate, very low potash	FAO, 2019; MoALD, 2021;
	Bangladesh	No national guideline	Nitrogen dominance; moderate phosphate; widespread potassium deficiency	Rahman et al., 2022; FAO, 2023
	Pakistan	No national guideline	High nitrogen application; Low phosphate and potassium use across major crops	FAO, 2019; NFDC, 2020;

4.3 Ammonia emissions and $PM_{2.5}$ formation

Ammonia volatilised from fertilisers and manure are a major precursor of secondary $PM_{2.5}$ (Kuttippurath et al., 2020). Once released, gaseous NH_3 reacts with acidic gases such as nitrogen dioxide (NO_x) and sulphur dioxide (SO_2) to form fine aerosol particles like ammonium nitrate (NH_4NO_3) and ammonium sulphate ($(NH_4)2SO_4$), which constitute substantial portion of secondary inorganic aerosols in South Asia (Cao et al., 2017). Satellite observations and modelling consistently identify the IGP as one of the world's largest agricultural NH_3 hotspots due to intensive fertiliser use (Pawar et al., 2021). Recent emission inversion analysis further confirms high anthropogenic ammonia emissions across South Asia and highlights their importance in regional $PM_{2.5}$ formation (Xia et al., 2025).

Integrated assessments conducted using the GAINS model reveal that secondary precursor emissions, specifically agricultural ammonia, are critical drivers of air pollution in South Asia. In 2015, these precursors were responsible for approximately 33%–54% of $PM_{2.5}$ concentrations across the Indian states of IGP (Purohit et al., 2019). Regional chemical-transport modelling estimates that NH_3 emissions account for about 11% of annual mean $PM_{2.5}$ across South Asia, with agricultural ammonia contributing around 10–15 micrograms of $PM_{2.5}$ in per cubic meter of air ($\mu g/m^3$) in the IGP hotspots (Wang et al., 2025).

Secondary inorganic aerosols, particularly ammonium sulphate formed from SO_2 and NH_3, contribute up to one-third of the $PM_{2.5}$ burden, significantly influencing the severity of winter pollution episodes (CREA, 2025). Across the IGP, the quantitative impact of agricultural ammonia varies across sub-regions but remains substantial throughout. Table 2 summarises source-apportioned $PM_{2.5}$ concentration projections derived from GAINS model estimates and regional inventories.

$PM_{2.5}$ emissions from fertilisers versus crop residue burning

As shown in Figure 1, $PM_{2.5}$ contributions from crop residue burning (CRB) is projected to decline across some major pollution hotspots in India, Pakistan and Bangladesh, between 2021 and 2035. For example, Punjab (India), CRB-related $PM_{2.5}$ is projected to decrease from approximately 8 $\mu g/m^3$ in 2021 to about 7 $\mu g/m^3$ in 2035, with similar reductions likely in the Indian states of Haryana, Delhi, Uttar Pradesh, Bihar, and in Dhaka, Bangladesh. This declining trend could be potentially due to effective implementation of existing policies, including increased mechanisation and promotion of alternative crop residue management practices for controlling stubble burning, and stricter enforcement of burning bans, among other things.

In contrast, Figure 2 reveals that projected $PM_{2.5}$ contributions linked to fertiliser use exhibit an upward trajectory in nearly all locations, except for

TABLE 2 REGIONAL $PM_{2.5}$ CONCENTRATION PROJECTIONS BY SOURCE (2021 VS. 2035)

Region / State	Fertiliser $PM_{2.5}$ (2021) ug/m$_3$	Crop Residue Burning $PM_{2.5}$ (2021) ug/m^3	Total $PM_{2.5}$ (2021) ug/m$_3$	Fertiliser $PM_{2.5}$ (2035) ug/m$_3$	Crop Residue $PM_{2.5}$ (2035) ug/m$_3$	Total $PM_{2.5}$ (2035) ug/m$_3$
Punjab (Pakistan)	1.1	2.2	34.1	0.9	1.8	31.2
Punjab (India)	3.3	8.2	54.9	3.4	7.5	54.3
Haryana (India)	3.1	7.6	69.3	3.4	7	63.6
Delhi (India)	2.6	5.2	98.2	2.9	4.9	83.9
Uttar Pradesh (India)	2.9	4.2	63.3	3.3	3.9	56.9
Bihar (India)	2.9	3.0	62.3	3.1	2.8	54.2
Jharkhand (India)	1.4	1.7	51.1	1.6	1.6	51.3
West Bengal (India)	1.8	2.6	63.5	2.2	2.4	59.8
Nepal (Terai)	0.7	1.4	28.5	0.9	1.8	31.2
Dhaka (Bangladesh)	1.3	7.8	93.3	1.8	6.9	85.4
Rest of Bangladesh	0.5	6.2	42.6	1.4	6.2	38.2

Source: GAINS model, IIASA

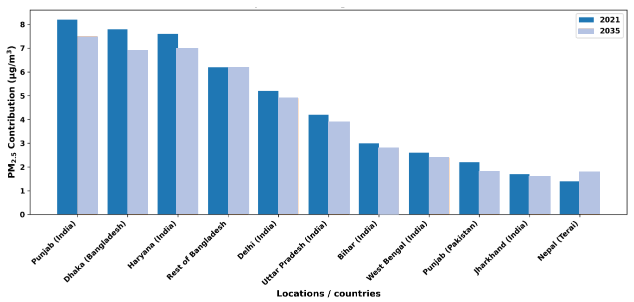
a marginal decline in Punjab (Pakistan). Notable increases between 2021 and 2035 are projected for Haryana and Delhi, while Bihar, Jharkhand and West Bengal in India, the Terai region in Nepal, and Bangladesh exhibit similar growth trends. This rising trend in fertiliser-related emissions, , remain largely unaddressed within existing policy frameworks.

Based on the GAINS source-apportionment ambient contribution data, comparative bar charts for 2021 and 2035 show a widespread decline in $PM_{2.5}$ from CRB across all regions, while fertiliser-related $PM_{2.5}$ increases in nearly every region, with the sole exception of Punjab (Pakistan). This divergence indicates that policy efforts and resources have been disproportionately focused on stubble burning, yielding projected air-quality improvements, whereas fertiliser management has remained comparatively under-addressed, allowing emissions to grow. Without parallel interventions targeting fertiliser-related emissions, the net reductions in ambient $PM_{2.5}$ are likely to be limited or partially offset.

4.4 Smog and regional air pollution

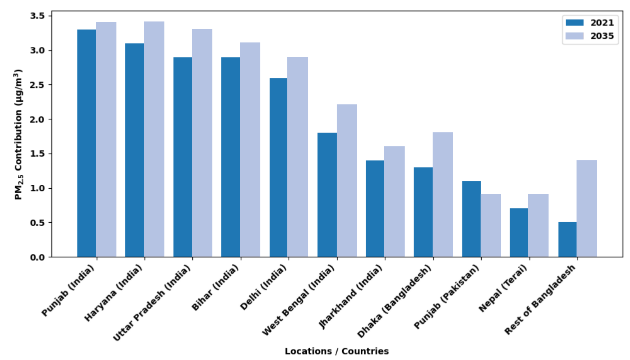
The IGP region experiences persistent wintertime temperature inversions, low wind speeds, and shallow boundary layers, creating conditions highly conductive to the accumulation of $PM_{2.5}$ and the formation of secondary aerosols (Ojha et al., 2020). Under these stagnant conditions, NH_3 emissions from fertiliser application and livestock management become a major contributor to secondary inorganic aerosol formation, particularly during severe winter haze episodes (Acharja et al., 2022). Recent atmospheric

FIGURE 1 PROJECTED CONTRIBUTION OF CROP RESIDUE BURNING TO AMBIENT $PM_{2.5}$ CONCENTRATIONS (2021 VS. 2035)



Source: GAINS model, IIASA

FIGURE 2 PROJECTED CONTRIBUTION OF FERTILISER USE TO AMBIENT $PM_{2.5}$ CONCENTRATIONS (2021 VS. 2035)



Source: GAINS model, IIASA

modelling indicates that excess ammonia in the IGP enhances the formation of ammonium-based particles, thereby sustaining elevated $PM_{2.5}$ levels even as combustion-related NO_x and SO_2 emissions decline. This dynamic effectively imposes an ammonia-driven limit on the effectiveness of traditional air-pollution control strategies (Pawar et al., 2023).

Collectively, these findings demonstrate that wintertime smog across the IGP is increasingly governed by ammonia-rich secondary aerosol formation, underscoring the necessity of controlling agricultural NH_3 emissions to achieve substantial and sustained improvements in regional air quality.

4.5 Why addressing nitrogen overuse is central to air-quality policy

Despite growing scientific evidence, agricultural NH_3 emissions remain largely overlooked in mainstream air-quality governance across the IGP-HF region. Analyses at the South Asia scale show that NH_3 emissions from agriculture is a major contributor to ambient $PM_{2.5}$, underscoring that the reductions in traditional combustion sources alone are unlikely to achieve expected air-quality improvements without parallel action on NH_3 (Wang et al., 2024).

Current national and regional frameworks, including clean air programmes, tend to focus on visible urban pollution sources, such as dust, vehicular, industrial, and construction emissions, often leaving the chemical precursors of secondary $PM_{2.5}$ largely unaddressed (Purohit et al., 2024). As a result, persistent NH_3 emissions from fertiliser overuse, manure application, and livestock continue to act as a hidden driver of haze and poor air quality in non-attainment cities across the IGP-HF region. Hence, to achieve meaningful and sustained $PM_{2.5}$ reductions and associated health benefits, air-quality policy must expand beyond urban source controls to include stringent regulation and management of nitrogen use and agricultural NH_3 emissions across the entire IGP-HF region.

The IGP-HF region operates as a chemically interconnected airshed, influenced by wintertime inversions, low boundary-layer heights, and an “ammonia-rich” atmospheric regime. In this context, excess NH3 fertilisation acts as a chemical catalyst, reacting rapidly with even reduced levels of NO_x and SO_2, to form ammonium nitrate and ammonium sulphate. This creates an “ammonia ceiling,” whereby abundant NH_3 sustains high $PM_{2.5}$ levels and limits the effectiveness of traditional combustion-focused pollution controls (World Bank, 2023).

FIGURE 3 NATIONAL CLEAN AIR POLICIES IN THE IGP-HF REGION IN A SNAPSHOT

India’s NCAP targets 131 non-attainment cities with a strong emphasis on road dust and vehicular emissions, while treating agriculture primarily through the lens of crop-residue burning rather than nitrogen-use efficiency (MoEFCC, 2019).

Pakistan’s Punjab Clean Air Policy prioritises brick kiln reform and burning controls but lacks mechanisms to regulate volatilised ammonia from livestock and urea application (GoP, 2023).

Nepal’s Kathmandu Valley Air Quality Management Action Plan focuses on vehicle testing, waste burning, and brick kilns, with minimal linkage to fertiliser use and NH_3 transport from the Terai plains (MoFE, 2020).

Bangladesh’s Air Pollution Control Rules (2022) centre on industrial compliance and dust management while overlooking ammonia emissions from deltaic rice systems and intensive fertiliser use (DoE, 2022).

A review of national clean air strategies across the region consistently reveals a blind spot regarding ammonia and nitrogen management. As shown in Figure 3, while current policies extensively address primary pollutants, an overview of the national clean air policies for countries in the IGP-HF region reveals that such policies are heavily skewed towardss transport, industry, and dust management, vis-à-vis agricultural nitrogen management, which is literally missing in the policy frameworks. Consequently, they lack specific regulatory mechanisms or quantitative targets for agricultural NH3 mitigation. This policy gap underscores the disconnect between atmospheric science and sectoral governance, leaving the region’s most significant secondary precursor largely unregulated.

Despite sharing a contiguous airshed, these national approaches remain fragmented and overwhelmingly urban-centric. This mismatch between atmospheric chemistry and governance priorities has created a transboundary mitigation trap: substantial investments in dust, industrial, and transport controls yield diminishing returns because the dominant precursor, agricultural NH3, remains largely unregulated. As long as NH_3 emissions stay high, they continue to sustain secondary $PM_{2.5}$ across the IGP-HF, effectively offsetting gains achieved in other sectors (Amann et al., 2017; World Bank, 2023).

Achieving meaningful and sustained $PM_{2.5}$ reduction in the IGP-HF region, therefore, requires a strategic shift: air quality governance must expand beyond urban-source controls to include nitrogen use efficiency, comprehensive fertiliser management, and systematic regulation of agricultural NH_3 emissions across the entire transboundary airshed.

SECTION V

International policies and praxis for agricultural nitrogen governance

Improving nitrogen use efficiency and reducing agricultural NH3 emissions have become key policy priorities worldwide. Several countries have demonstrated that integrated approaches, combining regulatory controls, economic incentives, advanced agronomic practices, and technological interventions, can simultaneously enhance air quality, enhance soil fertility, and sustain crop productivity. Table 3 provides a comparative assessment of global policies and technological interventions for mitigating agricultural NH_3 emissions and optimising nitrogen use, highlighting the range of strategies adopted and their respective outcomes.

5.1 Improving nitrogen use efficiency and ammonia emissions: Global best practices

China's adoption of a comprehensive "package" approach and cost-effectiveness strategy represents one of the most ambitious nitrogen-management strategy globally. Rather than relying on single interventions, this bundled strategy integrates the "4Rs" principles of nutrient stewardship: Right Rate, Right Type, Right Time, and Right Place, with advanced agronomic technologies, such as enhanced efficiency fertilisers (EEFs) and deep-placement application machinery.

To enable large-scale adoption, China has complemented these technical measures with targeted socio-economic instruments, most notably the proposed nitrogen credit system (NCS), which subsidises farmers for adopting nitrogen-efficient practices and technologies. Empirical evidence suggests that this integrated mitigation strategy is highly cost-effective: the combined societal benefits spanning public health improvements, climate mitigation, and ecosystem protection outweigh implementation costs by an estimated ratio of 25:1 (Gu et al., 2023).

Decoupling productivity from nitrogen application

To understand the trajectory of the IGP-HF region, requires situating its fertiliser-use intensity within a global context. Comparative analyses show that China has historically ranked among the world's highest consumers of nitrogen fertiliser per hectare. However, following the introduction of its "zero-growth" and efficiency-oriented policies, China has successfully initiated a decoupling trend, where fertiliser use has stabilised or declined while crop yields have continued to rise (Zhang et al., 2013; Cui et al., 2018).

Table 4 presents a comparative overview of nitrogen fertiliser rates across major agricultural economies. While China's fertiliser intensity remains higher than the global average and that of countries such as the United States and India, its recent downward trajectory demonstrates that high agricultural productivity can be maintained without continued growth in nitrogen inputs.

TABLE 3	COMPARATIVE ASSESSMENT OF GLOBAL POLICIES AND TECHNOLOGICAL INTERVENTION FOR AGRICULTURE NH3 AND NITROGEN MITIGATION.

Country/ Region	Policy/Regulation/Practice	Outcomes	References
European Union	**1. NEC Directive (2016/2284)** Sets legally binding national reduction commitments for 5 key pollutants, including NH_3. **2. Code of Good Agricultural Practice** Promotes specific low-emission techniques across member states. Encourages replacing Urea with Ammonium Nitrate (which has lower volatility) or using urease inhibitors. Promotes slurry injection and trailing-shoe application over surface broadcasting. Mandates farmer training on nutrient management.	The Directive successfully halted the historical rise in ammonia emissions. Emissions have decreased by 16% between 2005 and 2022. Although this reduction is slower compared to other pollutants (like Sulphur), it confirms that the regulatory framework is working.	EEA, 2024
Germany	**1. The Fertiliser Ordinance (DüV)**: Strict national law that mandates two key practices: **Urea Rules**: Urea fertiliser must be applied with urease inhibitors OR incorporated into the soil within 4 hours of application. **Manure Rules**: Broadcast spreading of liquid manure is banned. Farmers must use low emission spreading techniques (e.g., trailing shoe, trailing hose, or direct injection) that place nutrients directly at the soil root zone.	Between 2016 and 2021, these measures led to a significant drop in NH_3 emissions. Urea-related NH_3 emissions fell by approx. 83%. Germany successfully reversed its rising emission trend to meet EU NEC Directive targets.	Umwelt-bundesamt, 2023
France	**1. PREPA & Equipment Subsidies**: Under the *National Plan for Reduction of Atmospheric Pollutants (PREPA)*, France enforces: **Incorporation Rules**: Solid manure must be incorporated into the soil within 12-24 hours (depending on the zone). **Equipment Grants**: The government (via ADEME and "France Relance") provides heavy subsidies for farmers to purchase low emission spreading equipment (pendillards/trailing hoses and injectors), phasing out broadcast "splash plates."	The national assessment confirms that switching from broadcasting to trailing hoses reduces emissions by 30% -60%, and to direct injection by up to 90%. While technology adoption is increasing, national total ammonia emissions have remained relatively stable (-2% trend), prompting calls for stricter mandatory enforcement rather than just subsidies.	ADEME, 2020
Denmark	**1. Technology-Based Mandates**: Strict national legislation requiring specific "Best Available Techniques" (BAT) for all significant livestock farms: **Slurry Acidification**: A unique Danish mandate promoting the addition of sulfuric acid to liquid manure (either in-house or during application) to lower pH and prevent ammonia vaporization. **Application Rules**: Mandatory direct injection of slurry into soil or usage of trailing hoses; broadcast spreading is banned.	Denmark maintains one of the most successful reduction records in Europe. Ammonia emissions decreased by approximately 45% between 1990 and 2022. This reduction was achieved despite a simultaneous increase in agricultural production, effectively decoupling high output from environmental impact.	Nielsen et al., 2024
Netherlands	1. **The Nitrogen Law & Crisis Management**: Stringent national legislation driven by the EU Habitats Directive, aiming for a 50% reduction in nitrogen emissions by 2030. 2. Mandatory Technologies: **Manure Injection**: A total ban on surface spreading; farmers must use sod-injection or slit-coulter systems.	Ammonia emissions have dropped by approx. 62% since 1990, the highest reduction in the EU.	Honig & Montfoort, 2024
United States	**Voluntary Incentive Model**: Unlike the EU, federal policy relies on financial incentives rather than strict caps: **EQIP Funding**: The Environmental Quality Incentives Program (EQIP) provides cost-sharing (subsidies) to farmers who voluntarily adopt conservation practices. **Standard 590**: The NRCS Nutrient Management Conservation Practice Standard (Code 590) guides farmers on the "4Rs" (Right Source, Rate, Time, Place) to minimize loss.	Farms participating in NRCS programs show measurable reductions in nitrogen runoff and volatilisation. However, because participation is voluntary, aggregate national ammonia emissions have remained flat or slightly increased in recent years, contrasting with the reductions seen in regulated regions like Denmark.	USDA, 2024
United Kingdom (England)	1. **"Option 4" (Red Tractor Scheme)**: New industry-led regulations effective from 2024: **Urea Restriction**: Farmers must use urea treated with a urease inhibitor. **Exemption Window**: Untreated urea is only permitted if applied between Jan 15 and Mar 31 (when cold temperatures naturally limit volatilisation). **Enforcement**: Compliance is monitored via Red Tractor farm assurance audits rather than direct government inspections. 2. **Clean Air Strategy**: Specific targets to reduce ammonia emissions by 16% by 2030 (vs 2005 baseline).	The new urea rules are projected to deliver an ammonia reduction of approx. 11.2 kilotons (kt) per year. The latest inventory confirms that agriculture contributes 87% of UK ammonia emissions, with urea fertiliser being a primary hotspot that this new policy directly targets.	Carswell et al., 2024
China	1. **Cost-Effective "Package" Approach**: Adoption of a bundled strategy combining Right 4Rs (Rate, Type, Time, Place) with advanced technologies: **Technological**: Usage of Enhanced-Efficiency Fertilisers (EEFs) and deep placement machinery. **Socio-Economic Enabler**: Proposed implementation of a **"Nitrogen Credit System" (NCS)** to subsidize the cost for farmers, incentivizing adoption. Promoting larger farm sizes (land consolidation) to make advanced machinery financially viable.	The study establishes that nitrogen mitigation is highly cost-effective: A potential 32% reduction in total nitrogen loss (including NH_3 and runoff) is achievable. The societal benefits (health, climate, ecosystem) outweigh the implementation costs by a factor of 25 to 1. (Global estimate with China as a primary hotspot).	Gu et al., 2023
Japan	1. **MeaDRI Strategy (2021)**: A national roadmap aiming for a 30% reduction in chemical fertiliser use by 2050. It mandates: **Smart Agriculture**: Usage of robot tractors and "Variable Rate Application" machinery that adjusts fertiliser dosage in real time based on soil sensors. **Next-Gen Controlled Release**: Transitioning away from traditional plastic-coated urea (to prevent marine pollution) towards biodegradable coatings or deep placement technologies. **Tokubetsu Saibai**: Certification system for "Specially Cultivated Agricultural Products" that use 50% less nitrogen than regional standards.	Japan has successfully maintained high rice yields while steadily decreasing total nitrogen consumption. Over 80% of rice paddy area now utilises some form of labour-saving fertiliser technology (e.g., "One-shot basal application" which combines fertilization steps to reduce runoff risks).	MAFF, 2022

Nitrogen application rates in the IGP region are significantly higher than the global average of approximately 68 kg/ha (FAO, 2025), which helps explain why the region had emerged as a global hotspot for ammonia emissions. In countries such as Pakistan and India, nitrogen often accounts for over 70% of total nutrient application. This contrasts sharply with global trends, which increasingly emphasise balanced NPK fertilisation as a means of improving NUE.

China provides a compelling example of successful nitrogen management reform. National nitrogen application rates peaked to nearly 300 kg/ha in the early 2010s but have since declined substantially without compromising food security. This achievement was driven by efficiency-oriented policies and improved nutrient management practices, offering a valuable policy and technical template for the IGP-HF region.

Germany, by contrast, has pursued a strongly regulatory approach through its Fertiliser Ordinance (DüV), which mandates specific on-farm practices rather than relying solely on aggregate reduction targets. Key measures include the mandatory use of urease inhibitors with urea fertilisers or soil incorporation within four hours of application. Consequently, ammonia emissions from urea fertilisers dropped by approximately 83% between 2016 and 2021, reversing long-standing emission trends and enabling compliance with the EU National Emission Ceilings (NEC) Directive (Umweltbundesamt, 2023).

TABLE 4 COMPARATIVE NITROGEN FERTILISER USE PER HECTARE OF CROPLAND (2022-2023)

Country	Nitrogen Use (kg/ha)	Trend & Insight	Reference
China	191.55 kg/ha	Successful reduction since 2015 "Zero-Growth" policy; provides the template for regional decoupling.	Jin & Zhou, 2018; FAO, 2025
India	120.24 kg/ha	Rising trend: Nitrogen application remains the primary driver of nutrient imbalance in the IGP.	World Bank, 2023; FAO, 2025
Bangladesh	171.18 kg/ha	High application rate driven by intensive rice-cropping systems; characterised by strong N-dominance and widespread potassium deficiency	FAO, 2025
Pakistan	118.4 kg/ha	High N-application with low P and K use; major nitrogen surpluses observed in the Punjab and Sindh provinces.	FAO, 2025
Nepal	41 kg/ha	Skewed towards nitrogen due to market availability and high dependency on imports; lacks national guidelines on N:P: K ratios.	MoALD, 2021; FAO, 2025
United States	59 kg/ha	Maintains higher yields with lower N-intensity compared to Bangladesh and China through 4R precision stewardship.	USDA, 2022; UNFAO, 2025
World Average	68.0 kg/ha	Every country in the IGP-HF region significantly exceeds the global average, contributing to the regional "Ammonia Ceiling"	FAO, 2025

Driven by the EU Habitats Directive, the Netherlands has implemented one of the world's most stringent nitrogen-control regimes. The country enforces a total ban on surface broadcasting of manure and mandates the use of sod injection or slit coulter systems. Through these mandatory technologies and strict compliance, the Netherlands has achieved an estimated 62% reduction in ammonia emissions since 1990, the highest reduction recorded in the EU (Honig & Montfoort, 2024).

Denmark's policy framework relies on "Best Available Techniques" (BAT), specifically the mandate for slurry acidification and direct injection. By adding sulfuric acid to liquid manure to lower pH and prevent vaporisation, Denmark has decreased ammonia emissions by approximately 45% (1990-2022). Crucially, this reduction was achieved despite a simultaneous increase in agricultural production, effectively decoupling high output from environmental impact (Nielsen et al., 2024).

Japan's "Measures for achievement of Decarbonisation and Resilience with Innovation (MeaDRI) Strategy" (2021) focuses on smart agriculture, utilising robot tractors and variable rate machinery to adjust fertiliser dosage in real time. Over 80% of rice paddy area now utilises labour saving technology, allowing Japan to maintain high yields while decreasing nitrogen consumption (MAFF, 2022). In contrast, the United States relies on a voluntary incentive model through EQIP funding. While participating farms show reductions, aggregate national ammonia emissions have remained flat or slightly increased, contrasting with the reductions seen in regulated regions (USDA, 2024).

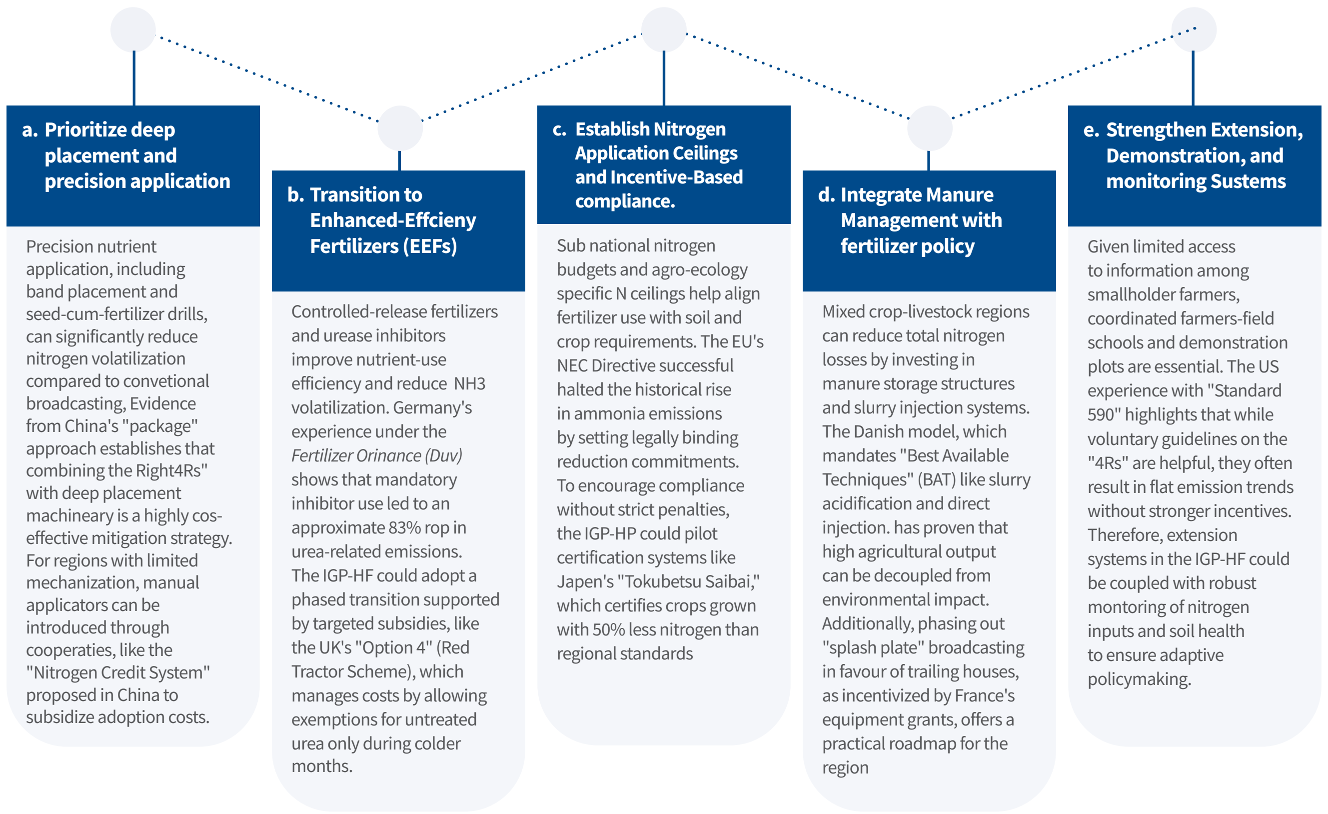
Collectively, global experiences show that nitrogen efficiency improvements lead to simultaneous benefits, reduced NH_3 emissions, improved air quality, improved soil health, and long-term agricultural sustainability. However, these global successes do not automatically translate to the IGP-HF region due to unique regional constraints. Effective implementation is primarily hindered by the dominance of smallholder farming systems and complex subsidy politics that often incentivise fertiliser overuse. Furthermore, chronic data gaps regarding real-time emissions and significant enforcement limitations within agricultural governance continue to obstruct the transition from global theory to local practice.

5.2 Key takeaways for the Indo-Gangetic Plain and the Himalayan Foothill region

The agricultural sector in IGP-HF region is broadly characterised by small and fragmented landholdings, diverse agro-ecologies, high nitrogen fertiliser dependency and weak enforcement capacity for agricultural nitrogen management. With these characteristics differing significantly from the aforesaid regions like China and Europe, direct adoption of their policies in the IGP-HF context is challenging. However, adaptation of these global best practices can be prioritised as follows:

- Adoption of enhanced-efficiency fertilisers such as Neem Plus urea, expansion of PM-PRANAM-style incentive programs, and strengthening rural ammonia monitoring networks. These can be implemented in the short-term using existing infrastructure and extension systems.

FIGURE 4 ADAPTATION OF GLOBAL BEST PRACTICES FOR THE IGP-HF REGION



- Institutional reforms such as establishing a National Nitrogen Authority, formalising IGP-HF airshed cooperation, and mainstreaming fertiliser use efficiency (FUE) into regional policy dialogues. These require additional governance structures, regional coordination, and capacity building.

By distinguishing short-term actionable steps from medium-term structural reforms, a regionally relevant strategy for the IGP-HF can be developed, enabling both immediate emission reductions and long-term sustainable nitrogen management as shown in Figure 4.

If implemented at scale, these interventions could reduce ammonia emissions in the IGP-HF by 40%-60%, increase NUE, and significantly reduce secondary $PM_{2.5}$ formation without compromising productivity.

However, the path to these outcomes requires a strategic shift. The IGP-HF region necessitates a China-style bundling of policies rather than relying on pure regulation or voluntary approaches. This framework must combine fiscal incentives, such as restructuring fertiliser subsidies to reward efficiency, with strict product-level mandates. For instance, a transition to "Neem Plus" or other enhanced efficiency fertilisers. By integrating economic support with mandatory technological standards, the region can effectively address the unique challenges of smallholder dominance and atmospheric chemistry to achieve sustained air-quality improvements.

CHAPTER VI

Policy gaps and challenges

Air quality governance across the IGP-HF region has seen institutional growth over the past decade, with countries like India introducing flagship programs (such as, the National Clean Air Programme (NCAP)) and establishing coordinating bodies (for example, the Commission for Air Quality Management (CAQM)). However, despite these efforts, the regional policy architecture suffers from a deep structural blind spot characterised by the near complete exclusion of NH3 and reactive nitrogen from regulatory and mitigation frameworks across the IGP-HF airshed.

This omission is not merely a technical oversight, but it represents a fundamental disconnect between scientific evidence on secondary aerosol chemistry and the design of the region's air quality instruments (Rudek et al., 2017). While substantial resources are dedicated to reducing visible, primary pollutants such as dust and soot, the gaseous precursors that drive secondary $PM_{2.5}$ formation especially NH3 remain largely unmanaged.

6.1 Structural exclusion of ammonia from regional strategies

Flagship strategies like India's NCAP, launched in 2019 to reduce particulate pollution, focus overwhelmingly on primary particulate matter, including road dust, construction debris, and combustion emissions from transport and industry (MoEFCC, 2019).

Crucially, secondary inorganic aerosols (ammonium sulphate and ammonium nitrate), which constitute a significant portion (30%-50%) of the $PM_{2.5}$ mass in cities across the IGP-HF region, are not addressed through specific, binding reduction targets in most national plans (CREA, 2024).

Specifically, the key missing elements in national level Clean Air Action Plans within the IGP-HF context include:

- Absence of any NH3 reduction target in national plans.
- Lack of mandates for incorporating urease inhibitors or improved fertiliser technologies that reduce NH3 volatilisation from agricultural land.
- No common regional enforcement mechanism for regulating agricultural emissions (World Bank, 2023).

Budget analyses show that in many national frameworks, a disproportionately small share of funds is allocated to precursor control, while the majority is spent on symptom management (mechanical sweepers, water sprinklers, and dust control) (CSE, 2024). This structural emphasis leaves the chemical "reactor" of the Indo-Gangetic Plain active and functioning across borders, even as individual cities and countries attempt to treat the symptoms of pollution locally. Addressing the transboundary challenge of NH3 is essential for the entire IGP-HF region to effectively reduce $PM_{2.5}$ concentrations.

6.2 National frameworks' jurisdictional mismatch for a regional pollutant

While ammonia is a transboundary pollutant (World Bank, 2023), primary air quality frameworks across the IGP-HF region, such as India's NCAP, Pakistan Punjab's Clean Air Policy, and Nepal's Kathmandu Valley Action Plan identify "non-attainment cities" based strictly on municipal boundaries. These frameworks mandate city action plans (CAPs) that apply only within urban jurisdictions, a design fundamentally incompatible with ammonia's transboundary behaviour.

Ammonia emissions originate overwhelmingly from rural fertiliser application and livestock, not from within municipal limits. Urban authorities, such as the Municipal Corporation of Delhi or the Commissioner of Lahore, can regulate construction dust and traffic, but they lack the mandate to regulate urea application or manure management in the agricultural districts surrounding Delhi, Lucknow, Lahore, or Kathmandu.

This creates a region-wide governance paradox with the source of pollution (rural farmers) being outside the jurisdiction of city governments, while the victims of pollution - the urban residents – are within the city jurisdiction. This city boundary logic, thus, creates a "regulatory wall" that undermines the airshed reality. By treating air pollution as a series of isolated urban problems rather than a regional rural urban continuum, these frameworks undermine their own ability to address the long-range transport of ammonia, which drives secondary $PM_{2.5}$ formation across the IGP-HF region (GoP, 2023; World Bank, 2023).

6.3 Fragmented governance of the nitrogen cycle

Nitrogen governance across the IGP-HF region is deeply fragmented across ministries with conflicting mandates. While the scientific consensus emphasises the need for a unified nitrogen policy, the administrative reality in India, Pakistan, Nepal, and Bangladesh is one of rigid "departmental silos." As the Indian Nitrogen Assessment highlights, this institutional fragmentation is a core barrier to managing reactive nitrogen (Nr) effectively (Abrol et al., 2017). This governance disconnect creates a "policy tug of war" visible across all major IGP economies:

- Ministries like India's and Bangladesh's Ministry of Environment, Forest and Climate Change (MoEFCC), Pakistan's Ministry of Climate Change (MoCC), and Nepal's Ministry of Forests and Environment (MoFE), treat ammonia purely as a hazardous air pollutant. They set ambient standards and monitor air quality but lack the legal authority to intervene in agricultural practices or fertiliser usage in rural areas (Abrol et al., 2017).
- Conversely, ministries of agriculture across several IGP-HF countries (for instance, India's Ministry of Agriculture and Farmers' Welfare (MoA&FW), Bangladesh Ministry of Agriculture, and Pakistan's Ministry of National Food Security and Research (MNFSR)) view nitrogen solely as an input for food security. They heavily subsidise urea to ensure crop yields, particularly for water intensive crops like paddy, inadvertently incentivising nitrogen overuse and creating a "leakage" of nitrogen into the air and water (Sutton et al., 2011).

There is no single body responsible for the full nitrogen cycle from production and import to soil application and atmospheric loss. This results in mutually contradictory policy signals, one arm of the government tries to control pollution (via Clean Air Acts) while another arm actively subsidises its source (via urea subsidies). This incoherence ensures that pollution control efforts are perpetually undermined by agricultural policy across the entire airshed (Raghuram et al., 2021).

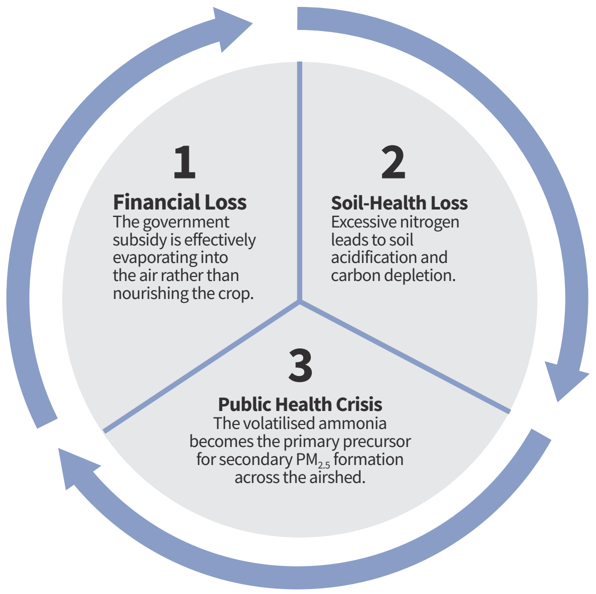
6.4 The fertiliser subsidy trap

Across IGP, urea is not treated merely as an agricultural input, but as a politically sensitive commodity essential for food security. In countries like India, Bangladesh, and Pakistan, urea is heavily subsidised, often sold at just 10%-20% of its international market price. This deep price distortion makes nitrogen the cheapest nutrient available, encouraging massive overuse compared to phosphorus or potassium (Gulati et al., 2021).

This economic structure creates a "usage trap." Farmers across IGP perceive this cheap urea as low-cost insurance against yield loss, applying it indiscriminately without considering diminishing returns or soil health. However, in the specific agro-climatic conditions of IGP characterised by alkaline soils, high ambient temperatures, and flood irrigation practices, a significant percentage of this surface applied urea volatilises as ammonia gas (NH_3) within days of application (Sutton et al., 2011). This volatilisation represents a triple loss as shown in Figure 5.

Despite this, the current administrative databases in these countries track fertiliser sales (to calculate subsidy payouts) rather than nitrogen use efficiency (NUE) or soil-specific limits. This data gap allows nitrogen overuse to continue unchecked, as the metric for success is currently "volume sold" rather than "efficiently used" (Abrol et al., 2017; World Bank, 2023).

FIGURE 4 ADAPTATION OF GLOBAL BEST PRACTICES FOR THE IGP-HF REGION



6.5 Public attention and the "burning myopia"

Public discourse and judicial interventions in the IGP-HF region are heavily skewed towardss crop residue burning, creating a phenomenon of "burning myopia." While stubble burning is a visible, episodic event restricted to the post-harvest weeks, ammonia emissions from fertiliser application are invisible, widespread, and sustained year-round.

Recent satellite-based inventories reveal a critical disconnect between the policy focus and the chemical reality:

a. **The seasonal mismatch**: Ammonia concentrations across IGP peak twice a year -once during the Kharif (July-August) sowing and again during Rabi (October-November) sowing seasons. The massive Kharif peak occurs during the monsoon when there is zero crop burning, proving that agriculture's dominant contribution to pollution is chemical (fertiliser) rather than thermal (fire) (Beale et al., 2022).

b. **The geographic blind spot**: While the media spotlight is fixed on the burning fields of Punjab and Haryana, the eastern IGP (India's Bihar and West Bengal, and Nepal's Terai region) exhibits consistently high ammonia loadings due to intensive urea application. These regions suffer from "silent" secondary aerosol formation that goes largely unnoticed by Delhi-centric media (Kuttippurath et al., 2020).

Despite this, most of the air quality funding such as India's Crop Residue Management (CRM) scheme is dedicated exclusively to machinery for stubble management. This leaves the larger, year-round source of fertiliser emissions completely unaddressed, trapping the region in a cycle where it fights the visible smoke but ignores the invisible gas that fuels the smog.

6.6 Monitoring deficit and the rural gap

Across the IGP-HF, air quality monitoring infrastructure suffers from a severe "urban bias." The placement of Continuous Ambient Air Quality Monitoring Stations (CAAQMS) in India, Pakistan, and Nepal is determined largely by population density and industrial clusters, prioritizing the detection of vehicular and industrial emissions over agricultural pollutants.

This structural design flaw creates a massive "monitoring deficit" regarding the nitrogen cycle:

a. **The rural blind spot**: While satellite data (e.g., IASI, CrIS) clearly identifies the rural agricultural belts of Indo Gangetic Plain (including both Indian and Pakistani Punjab, Haryana, and the trans-border Terai region of India and Nepal) as global ammonia hotspots, ground level monitoring in these areas is virtually non-existent. This means the region's primary chemical source zones remain unmapped and unvalidated by regulatory grade instruments (Kuttippurath et al., 2020).

b. **The transboundary data gap:** Urban monitors in cities like Delhi or Lahore are positioned to measure local pollution. They are largely incapable of distinguishing between locally generated emissions and the massive transboundary influx of ammonia drifting in from the rural hinterlands. Without rural "background" stations, city-level data cannot quantify the agricultural contribution to the urban airshed (World Bank, 2023).

c. **Calibration and measurement challenges**: Measuring gaseous ammonia is technically more demanding than measuring $PM_{2.5}$. Ammonia is highly reactive and "sticky," often adhering to inlet pipes and filters, which leads to under reporting. Independent audits have frequently flagged that even where NH3 sensors exist, maintenance protocols and calibration drifts often render the data unreliable for policymaking (Khan et al., 2022).

Improving air quality monitoring across rural and agricultural areas is both technically feasible and cost-effective. A tiered monitoring system utilising passive samplers and low-cost sensors (LCS) offers a practical, scalable alternative to expensive regulatory-grade stations (Rai et al., 2017). Passive samplers are particularly advantageous in the IGP-HF context; they are inexpensive, require no electrical infrastructure, and are scientifically validated for mapping spatial NH3 gradients over the expansive agricultural belts (Huf et al., 2023).

Furthermore, LCS networks can capture real-time temporal trends and have proven effective for tracking pollution spikes in resource-limited rural settings (WMO, 2024). When supported by a strategic number of high-accuracy "reference stations" for localisd calibration, this hybrid approach provides high-integrity "ground truth" data at a fraction of the traditional capital cost. This infrastructure is essential for shifting towardss evidence-based mitigation of agricultural emissions, which cannot be accurately informed by urban datasets alone.

Without a robust rural monitoring network to provide "ground truth," designing effective mitigation for agricultural emissions remains scientifically impossible. Policymakers are effectively flying blind, attempting to manage a regional chemical problem with strictly local, urban datasets.

6.7 Policy vacuum in the Indo-Gangetic Plain and Himalayan Foothills region

The Indo-Gangetic Plain and Himalayan Foothills (IGP-HF) constitute one of the world's largest continuous airsheds, spanning the sovereign territories of India, Pakistan, Nepal, and Bangladesh etc. While the atmosphere functions as a single fluid system where pollutants circulate freely, the governance of this region remains deeply fractured. There is currently no integrated regional framework or legally binding treaty to manage pollution across this contiguous zone (Rupakheti et al., 2019). This disconnect between the atmospheric reality and political boundaries has created a profound policy vacuum.

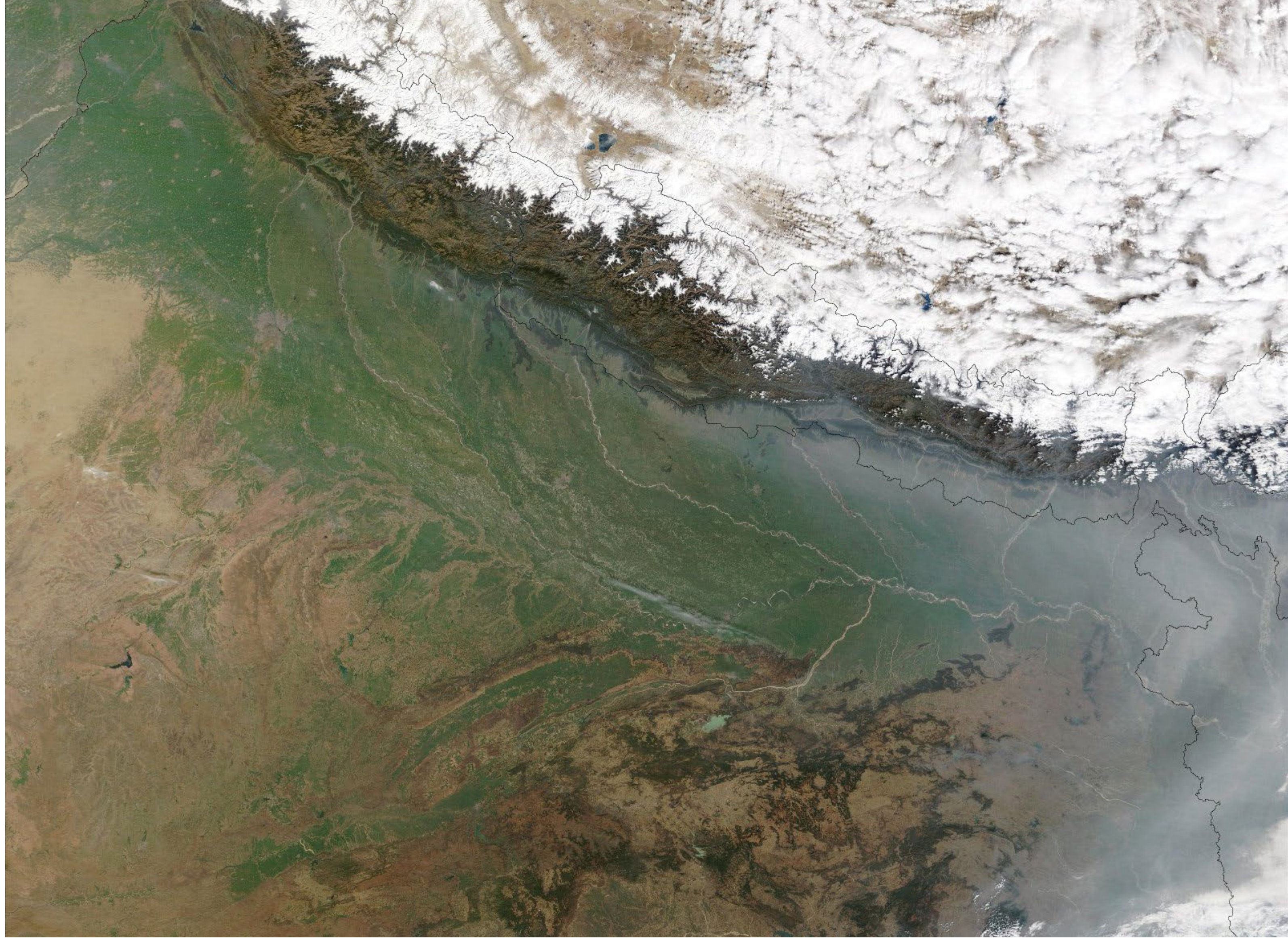
Key governance gaps include:

a. **Absence of transboundary protocols**: Unlike Europe, which manages cross-border pollution through the Convention on Long-Range Transboundary Air Pollution (CLRTAP), the IGP countries have no inter-state protocol to coordinate ammonia controls. There is no mechanism to manage shared agricultural plumes that drift from Pakistani Punjab into Indian Punjab, or from the Gangetic plains into the Nepali Himalayas (UNEP, 2019).

b. **The "national container" fallacy**: Frameworks like India's NCAP or Pakistan's Clean Air Policy do not recognise the airshed as the functional unit of management. They treat pollution as a domestic issue contained within national borders, ignoring the massive advective transport of precursors like NH3 (World Bank, 2023).

c. **Missing nitrogen ceilings**: Despite being signatories to the Colombo Declaration on Sustainable Nitrogen Management, none of the IGP countries have established a "national nitrogen ceiling" or a national-level limit on total reactive nitrogen (Nr) loading. This leaves the aggregate emissions of the region completely uncapped (Raghuram et al., 2021).

d. **Limited international cooperation**: Cooperation remains limited to ad-hoc scientific exchanges or non-binding declarations (e.g., the Malé Declaration). There is no permanent secretariat or joint commission empowered to enforce emission standards across the airshed.



The World Bank has repeatedly proposed an "airshed-based management" structure, arguing that achieving WHO air quality targets is mathematically impossible for any single city or nation acting in isolation. However, domestic policy has yet to adopt this perspective, leaving the region trapped in a cycle of localized, ineffective interventions (World Bank, 2023).

The transition from this policy vacuum towards a functional regional framework requires more than just political will. It demands a shift towards science-policy integration. This research report will explore potential solutions, ranging from the harmonisation of nitrogen standards to the establishment of a Regional Air Quality Commission, which could serve as the institutional backbone for the transboundary management of the IGP-HF airshed.

CHAPTER VII

Opportunities

The growing recognition of ammonia's role in sustaining $PM_{2.5}$ levels across the IGP-HF has opened a significant window for policy innovation. The launch of PM-PRANAM (India) in 2023, increasing international attention to airshed governance, technological advances in nitrogen-efficient fertilisers, and the emergence of state-level initiatives together present a unique opportunity to align agricultural policy with clean-air goals.

7.1 PM-PRANAM: A transformational opportunity for fertiliser governance

The PM Programme for Restoration, Awareness, Nourishment, and Amelioration of Mother Earth (PM-PRANAM) mark a fundamental shift in India's fertiliser governance paradigm. Unlike earlier subsidy regimes that rewarded fertiliser consumption, PM-PRANAM rewards fertiliser saving, creating a direct fiscal mechanism to incentivise efficiency.

7.1.1 How PM-PRANAM Works

Under the scheme, the central government calculates the fiscal savings generated when a state reduces its consumption of subsidised chemical fertilisers compared to the previous three-year average. The incentive structure is designed as follows:

- 50% of the calculated savings are returned to the state government as a grant.
- 70% of this grant is tied to asset creation and technological adoption, specifically for:
  - Setting up bio-fertiliser and bio-pesticide production units.
  - Establishing waste-to-energy and composting plants.
  - Strengthening soil health testing infrastructure.
  - Promoting alternative fertilisers (MoCF, 2023).
- 30% of the grant is untied and can be used to financially reward village panchayats, farmer producer organizations (FPOs), and individual progressive farmers who successfully demonstrate reduced fertiliser usage (MoCF, 2023).

This model serves as a rare example of eco-fiscal federalism, aligning state finances with environmental outcomes.

7.1.2 Early results (FY 2023–24)

The first year of PM-PRANAM implementation has yielded significant, measurable outcomes, demonstrating the scheme's potential to decouple agricultural productivity from chemical intensity. Official data tabled in Parliament confirms that 14 states successfully reduced their chemical fertiliser consumption against the baseline, triggering the release of subsidy savings as grants.

Key performance indicators (FY 2023-24):

- A total reduction of 15.14 Lakh Metric Tonnes (LMT) of chemical fertilisers was achieved across the participating states (MoCF, 2025).
- Karnataka emerged as the top-performing state, accounting for nearly 30% of the national reduction. This reduction was driven largely by the state's aggressive promotion of nano-urea and bio-stimulants during the kharif season (FAI, 2025).

TABLE 5 PM-PRANAM SNAPSHOT (FY 2023–24)

Metric	Outcome	Policy and environmental implication
Total fertiliser reduced	15.14 LMT	Represents a direct reduction in the NH_3 precursor pool, mitigating the "Ammonia Ceiling" effect in the airshed.
Participating states	14	Indicates high sub-national willingness to adopt fiscal incentives for soil health.
Top performer	Karnataka	Highlights the need to distinguish between policy-driven reduction (e.g., bio-input adoption) vs. climate-driven reduction (e.g., drought lowering sowing area) to ensure long-term sustainability.

- From an air-quality perspective, this 15.14 LMT reduction is critical. Considering that 18%–30% of applied urea nitrogen typically volatilises as NH_3 within 72 hours, this reduction translates into a massive avoided atmospheric load of reactive nitrogen, directly preventing secondary $PM_{2.5}$ formation.

7.1.3 Andhra Pradesh: The green direct benefit transfer model

Andhra Pradesh has created India's most innovative PM-PRANAM-linked mechanism through a "green direct benefit transfer" (Green DBT) for nitrogen reduction. Breaking away from the traditional model of subsidizing inputs, the state government announced a direct cash incentive for non-use.

- Farmers receive ₹800 per bag of urea they save compared to their historical baseline (Deccan Chronicle, 2025).
- With the market price of a subsidised urea bag at ~₹266, the cash incentive (₹800) is nearly 3x the cost of the fertiliser. This flips the economic logic, making conservation significantly more profitable than overuse.
- This intervention directly counters the "cheap insurance" bias. By monetising the "saved nitrogen," the state effectively pays the farmer for the ecosystem service of soil-health improvement and pollution reduction.

This model demonstrates how PM-PRANAM can be evolved from a purely fiscal instrument between the centre and the state governments into a farmer-centric behavioural tool, as originally envisioned in the state's natural farming roadmap, and how its "incentivising non-use" framework can be adapted across the IGP-HF to suit different governance structures:

- **Pakistan (Smart Subsidies)**: Transitioning from blanket price subsidies to "Smart Subsidies" delivered via the Kisan Card could mirror the PM-PRANAM reward system, focusing on districts with high NH3 volatilisation rates.
- **Nepal (Quota-Linked Incentives)**: Implementing incentives where local cooperatives receive infrastructure grants for meeting efficiency targets could address the Terai's nitrogen challenges.
- **Bangladesh (DAE-led PoPs)**: The Department of Agricultural Extension (DAE) can lead "package of practice" (PoP) shifts where subsidies are redirected towards specialised application equipment and training for precision farming.

7.2 Integrating fertiliser efficiency with clean air goals

Technological innovations offer a powerful pathway to decouple agricultural productivity from ammonia emissions, reducing the need for drastic behavioural changes from farmers. By embedding pollution control directly into the fertiliser product, the "mitigation burden" is shifted from the individual farmer to the manufacturing process.

7.2.1 The "Neem Plus" strategy: Upgrading from Neem-coated to N-(n-butyl) thiophosphoric triamide-coated urea

While India's mandatory Neem Coated Urea (NCU) policy was a positive step, it functions primarily as a *nitrification inhibitor* (slowing the conversion of ammonium to nitrate). It is less effective at stopping the initial hydrolysis step where urea turns into ammonia gas. The "Neem Plus" proposal advocates for a dual-coating mandate, retaining neem oil but adding a urease inhibitor (specifically NBPT: N-(n-butyl) thiophosphoric triamide).

- NBPT locks the urease enzyme, preventing it from breaking down urea on the soil surface. Meta-analyses confirm that NBPT-treated urea reduces ammonia volatilisation by approximately 52% to 70% compared to standard urea (Cantarella et al., 2018; Pan et al., 2016).
- Mandating "Neem Plus" acts as a technological silver bullet, slashing the source term of the region's secondary $PM_{2.5}$ without requiring farmers to change how they broadcast fertiliser.

7.2.2 Nano urea

Promoted by Indian farmer fertiliser cooperative and multiple fertiliser companies and supported by central policy, nano urea (Liquid) aims to replace bulk urea with foliar sprays, theoretically increasing NUE from 30%-40% of bulk urea to over 85% of nano urea.

- If successful, it offers a pathway to drastically reduce the total mass of nitrogen applied to the soil, thereby reducing the ammonia "leakage" into the air.
- However, the technology faces scientific scrutiny due to inconsistent outcome in field trials of nano urea product of IFFCO. Recent field bio-efficacy trials by state agricultural universities (e.g., Punjab Agricultural University (PAU)) and independent studies have flagged concerns regarding yield penalties (13%–21% reduction in rice/wheat) and lower grain protein content when bulk urea is aggressively replaced by IFFCO's nano urea (Mridha et al., 2025). On the other hand, nano urea product from TERI and Zuari Farm-Hub Limited was found to reduce bulk urea usage by 25% without having a negative impact on yield in the bio-efficacy field trials conducted by PAU and several other state universities (Singh et al., 2023).
- Policy support should pivot towards "rigorous validation" of nano fertilisers before mass substitution, ensuring that air quality goals do not compromise national food security.

7.2.3 Green ammonia

Under the National Green Hydrogen Mission (NGHM), India targets a production capacity of 5 million metric tonnes (MMT) of green hydrogen by 2030. Integrating this with the fertiliser sector is the most viable "early bird" application.

- NHGM proposes a mandate for fertiliser plants to blend green ammonia (produced via renewable energy) with conventional grey ammonia.
- While this helps decarbonise the production phase (CO_2), it does not solve the application phase (NH_3 volatilisation). Therefore, urea production by using green ammonia must be coupled with application of urea treated with urease inhibitors (Neem Plus) to reduce ammonia emission from fertiliser and agriculture sectors (MNRE, 2023).

7.3 The airshed solution: Institutionalising the framework for the Indo-Gangetic and Himalayan Foothill region

To bridge the IGP-HF policy vacuum, there is an urgent need to move beyond the national clean air programmes' (NCAP) city-specific focus towardss a transboundary "airshed management" approach. This requires shifting the unit of governance from administrative boundaries to atmospheric realities.

7.3.1 The "35-by-35" regional goal

Recent high-level policy dialogues in Bhutan, facilitated by the World Bank and ICIMOD, have proposed an aspirational goal for the IGP-HF region, reducing annual average $PM_{2.5}$concentrations to 35µg/m³ by 2035 (World Bank, 2024). Achieving this "35-by-35" target is scientifically impossible without addressing the regional ammonia pool.

- **Regional cooperation**: Solutions proposed include a «South Asian Transboundary Air Pollution Protocol,» modelled after Europe»s Convention on Long-range Transboundary Air Pollution (CLRTAP), which would set binding national emission ceilings for ammonia and facilitate data sharing between India, Pakistan, Nepal, and Bangladesh.
- **Integrated modelling**: The use of the GAINS model is being expanded to the entire IGP-HF region to quantify the benefits of synchronised ammonia reduction. Initial modelling suggests that coordinated action across the airshed reduces the cost of compliance significantly compared to unilateral state-level actions (World Bank, 2024).

Establishing an IGP-HF framework requires a clear governance structure to ensure it remains effective despite geopolitical shifts. To maintain technical continuity, the framework should be anchored by a Regional Air Quality Commission (RAQC) acting as a permanent secretariat. By hosting this body within established organizations like ICIMOD or South Asian Association for Regional Cooperation (SAARC) Environment Centre, standards for ammonia monitoring and emission data can remain consistent even during periods of strained political relations.

Political feasibility is maximized through a "science-first" diplomacy pathway that begins with low-stakes cooperation. This roadmap starts with joint scientific validation, such as shared satellite data, before moving to voluntary regional targets and eventually binding protocols. By reframing ammonia reduction as a matter of agricultural efficiency and food security, governments can find common ground through shared economic benefits. Additionally, empowering sub-national regions, like the two Punjab in India and Pakistan or the Terai-UP border between Nepal and India, to engage in "technical exchange corridors" allows for localised solutions without requiring immediate high-level treaties.

To prevent institutional overload, the transition to an airshed-based system follows a three-phased approach. The first phase focuses on data harmonization to align monitoring protocols. The second phase introduces voluntary cooperation by setting the "35-by-35" goal as a regional benchmark. The final phase moves into binding governance, where specific national nitrogen ceilings and the RAQC are codified into a formal inter-state protocol.

7.3.2 Airshed-based policy approaches

The Uttar Pradesh Clean Air Management Project (UPCAMP) represents how PM-PRANAM can be implemented at the state level to achieve air quality and climate co-benefits. UPCAMP's draft specifically targets agricultural and livestock emissions, which together contribute approximately 13% of ambient $PM_{2.5}$ in Uttar Pradesh (8% from fertiliser, 5% from livestock manure). The programme emphasises two priority objectives:

- Enhancing nitrogen use efficiency (NUE) in cropping systems and
- Promoting scientific livestock manure management.

UPCAMP purposes PM-PRANAM incentives by enrolling participating farmers in NUE pilot programs during its initial year. This ensures that state level air quality targets are both financially supported and behaviourally reinforced through central fiscal mechanisms.

The core intervention focuses on precision nutrient management practices (PNMPs) guided by the 4R Nutrient Stewardship framework, applied across multiple cropping systems. Over six years, UPCAMP aims to cover 48,000 hectares across 18 administrative divisions and nine agro-ecological zones, prioritising the 23 districts with critical nitrogen and phosphorus deficiencies.

7.4 Developing and scaling a region-specific "package of practices" (PoP)

To achieve a meaningful reduction in ammonia emissions without risking food security, the IGP-HF region must abandon the "one-size-fits-all" approach to fertiliser management. As highlighted by regional experts, generic NPK recommendations fail to account for the diverse soil realities spanning from the Indus plains to the Bengal delta. The region requires a transition to zone-specific package of practices (PoP) developed through rigorous pilot testing.

7.4.1 The "development pilot" strategy: Moving from generic to zonal

Current fertiliser guidelines across the IGP-HF are often too broad to be effective. A robust Package of Practices (PoP) must be customized for specific Agro-Ecological Zones (AEZs) to account for the diverse soil and climatic realities spanning from the Indus plains to the Bengal delta. While the Uttar Pradesh Clean Air Management Project (UPCAMP) provides a successful blueprint, the strategy must be scaled to the regional level to address the transboundary nature of the airshed.

The primary goal of these pilots is calibration, not just implementation. They serve to determine the precise combination of technologies such as deep placement, urease inhibitors, and optimised split application through usage of alternative and efficacious fertilisers that maximises nitrogen use efficiency (NUE) within a specific local ecology.

To transition this from a state-level initiative to a regional IGP-HF framework, the following scale is proposed:

- **Zonal coverage**: Implementation should be synchronised across the 15 major agro-climatic zones (ACZs) identified within the IGP-HF regional belt.
- **Target area per zone**: Each ACZ should host a "development pilot" covering approximately 5,000 to 6,000 hectares to ensure geographic representativeness and statistical validity.
- **Regional scaling phases**:
  - **Phase 1 (testing - years 2-3)**: Implementation on an initial 80,000 to 90,000 hectares across the 15 ACZs to test standard operating procedures (SOPs) and local technological compatibility.
  - **Phase 2 (validation - years 4-5)**: Scaling to a total of 160,000 to 180,000 hectares across the region to validate emission reduction data and yield stability before formal notification as the new standard agricultural advisory.

Once validated in these "living labs," these zonal PoPs will replace outdated, habit-based NPK ratios as the standard agricultural advisory for the entire region. By adopting this calibrated approach, the IGP-HF can replicate the success of global leaders, such as China, in decoupling agricultural productivity from total nitrogen consumption.

7.4.2 The "cluster approach" for institutional delivery

Even scientifically robust guidelines fail if the extension system is fragmented. To ensure effective delivery across the IGP-HF, a cluster approach anchored by local technical institutions is proposed to bridge the gap between regional research and smallholder application.

- **Institutional anchors: regional knowledge hubs**

  Village clusters should be formally linked to localised "knowledge hubs" that serve as the primary implementing agencies for training and oversight. These anchors vary by country but share the same mandate for technology transfer:

  India: The Krishi Vigyan Kendras (KVKs) serve as the frontline district-level institutional anchors, supported by State Agricultural Universities (SAUs) and ICAR institutes for scientific calibration.

  Nepal: Institutional delivery is anchored by Agriculture Knowledge Centers (AKCs) at the provincial level, which coordinate with Agriculture Service Centers (ASCs) and the Nepal Agricultural Research Council (NARC) for localised technology testing.

  Pakistan: Delivery is led by the Provincial Agriculture Extension Departments through Agricultural Extension Officers (AEOs) and Field Assistants, with scientific backing from the Pakistan Agricultural Research Council (PARC) and provincial adaptive research wings.

  Bangladesh: The Department of Agricultural Extension (DAE) utilises a block-level approach through Sub-Assistant Agriculture Officers (SAAOs) (formerly Block Supervisors), supported by the Bangladesh Agricultural Research Institute (BARI) for technical vetting.

- **Farmer collectivisation: scaling through shared economies**

  Smallholders across the IGP-HF often hold less than 2 hectares, making individual investment in advanced mitigation machinery (e.g., pneumatic planters for deep fertiliser placement) unviable. The strategy relies on organising farmers into formal collectives to facilitate shared technology use and efficient input procurement:

  Farmer producer organisations (FPOs) and cooperatives: The model suggests federating approximately 2,500 farmers per collective (FPOs in India, agriculture cooperatives in Nepal, and Common Interest Groups (CIGs) in Bangladesh).

  Custom hiring centres (CHCs): Collectives should operate CHCs to provide smallholders with affordable, fee-based access to precision nutrient management tools, laser land levellers, and deep-placement drills.

  Targeted outreach: These groups must prioritize the inclusion of women farmers (e.g., through Krishi Sakhis in India or Mahila Krishak groups in Nepal) who are frequently responsible for fertiliser application but often lack direct access to extension services.

7.4.3 Bridging the "incentive gap": from state savings to farmer action

A critical barrier to adoption across the Indo-Gangetic Plain–Himalayan Foothills (IGP-HF) is the systemic incentive mismatch. While fiscal reforms reward governments for reducing total fertiliser subsidies, the individual smallholder farmer who bears the immediate risk of yield loss often sees no direct financial benefit from reducing urea application.

To bridge this gap, the following regional incentive pathways are proposed:

India: The "Green DBT" model: Scale the precedent set by the UPCAMP and Andhra Pradesh pilots, which allocate direct cash incentives—such as ₹5,000 per hectare – directly to farmers who successfully adopt low-emission package of practices (PoP).

Pakistan: digital smart subsidies: Replicate the Kissan Card and e-voucher system used in the Punjab and Sindh provinces to modernize agricultural support. This digital system allows for "targeted subsidies" where financial support can be steered towards balanced blended fertilisers and micronutrients instead of blanket urea application, ensuring the benefit reaches the registered cultivator directly.

Nepal: interest subsidies and input quotas: Since Nepal's fertiliser supply is often quota-driven, incentives should be integrated into the Agriculture Loan framework. Providing a 5% interest subsidy on loans for farmers who participate in "Soil Health Credit" programs can mitigate the financial risk of transitioning to alternative and high-efficiency inputs like bio-fertilisers or urease inhibitors.

Bangladesh: targeted cash incentives for balanced use: Reallocate portions of the existing universal urea subsidy towards performance-based payments managed through the Department of Agricultural Extension (DAE). These payments should be conditioned on the adoption of the 4R framework (Right Source, Rate, Time, and Place) to correct the current over-application of nitrogen.

Strategic goal: regional decoupling of nitrogen consumption and yield: The ultimate objective for all regional member countries is to replicate the trajectory of nations like China, where agricultural productivity has been successfully decoupled from nitrogen consumption. This ensures that crop yields continue to rise while the total atmospheric nitrogen load is capped, protecting both food security and regional air quality.

By converting "saved nitrogen" into a farm-level asset, regional governments can transform fertiliser efficiency from an environmental burden into a profitable economic opportunity for the millions of smallholders sharing the IGP-HF airshed.

7.5 Technological pathways for high NUE and low emissions

Achieving substantial reductions in NH_3 volatilisation requires a combination of innovative fertilisers and targeted nutrient management:

7.5.1 Enhanced efficiency fertilisers (EEFs)

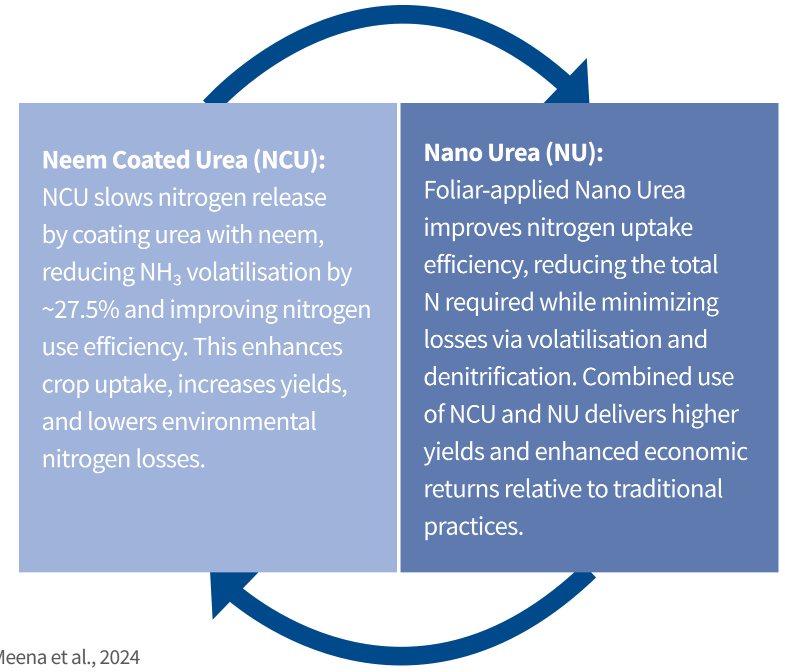
EEFs play a central role in reducing nitrogen losses as shown in Figure 6:

7.5.2 Precision nutrient management practices (PNMPs)

PNMPs shift fertilization from generalized broadcast methods to site-specific, adaptive management enabling farmers to match nutrient supply with crop demand more accurately. As Shown in Figure 7, these practices integrate real-time soil diagnostics, controlled-release inputs, and decision-support tools to optimise nutrient-use efficiency while minimising losses to the environment.

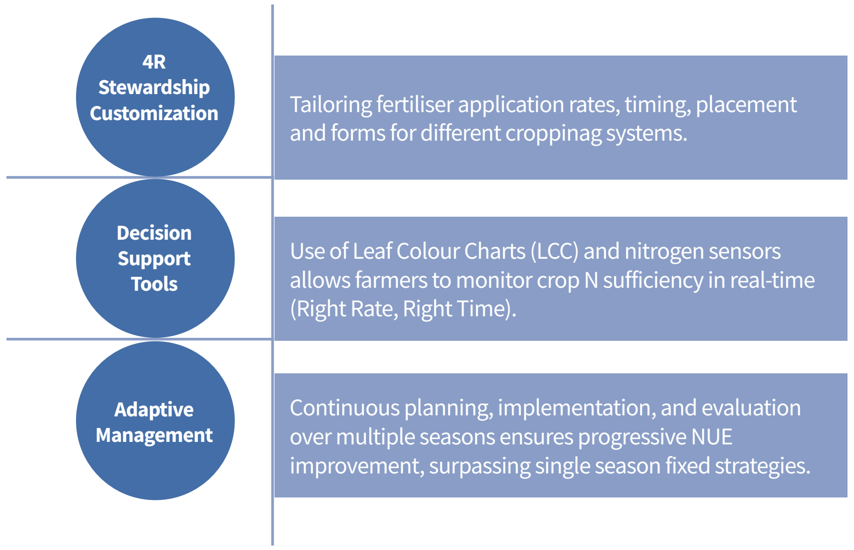
These practices directly mitigate NH_3 emissions, contributing to lower secondary $PM_{2.5}$ formation and generating hidden climate co-benefits by reducing N_2O emissions, a potent greenhouse gas.

FIGURE 6 MECHANISMS OF NITROGEN LOSS REDUCTION BY EEFS.



Source: Santhosh et al., 2023; Meena et al., 2024

FIGURE 7 FRAMEWORK OF PRECISION NITROGEN MANAGEMENT PRACTICES (PNMPS)



7.6 Policy incentives and institutional scaling

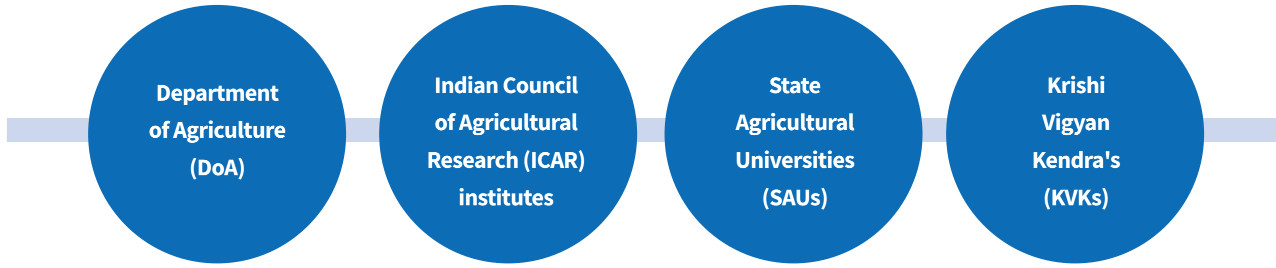
UPCAMP employs a multi-institutional approach as shown in Figure 8, involving coordinated engagement of state agriculture departments, research institutions, extension agencies, Panchayati Raj institutions, Farmer Producer Organizations (FPOs), and private-sector partners. This integrated structure ensures that policy incentives are effectively translated into scalable, field-level adoption of nutrient-efficient practices.

Given that 92% of UP farmers are small or medium holders (<2 ha), monetary support is critical for adoption. Additionally, UPCAMP dedicates approximately INR 592 Lakhs for awareness campaigns, training, and exposure visits for KVK staff, extension officers and farmers, ensuring knowledge transfer for successful PNMP implementation.

7.7 Developing a robust Monitoring, Reporting and Verification system for establishing baseline and monitoring impacts

A core innovation of UPCAMP, critical for linking PM-PRANAM fiscal incentives to measurable environmental outcomes, is the development of a robust Monitoring, Reporting and Verification (MRV) system. Historically, Indian agriculture has suffered from a lack of large-scale, high-quality emission measurement data, making it challenging to assess the effectiveness of interventions. Establishing a rigorous baseline is therefore essential to quantify improvements in nitrogen-use efficiency and reductions in NH_3 and greenhouse gas (GHG) emissions. The UPCAMP MRV system integrates two primary tiers of measurement, as outlined below:

FIGURE 8 APPLICATION STRATEGIES FOR THE 4R PRINCIPLES OF PRECISION NUTRIENT MANAGEMENT



7.7.1 Agronomic metrics

The efficiency gains from Precision Nutrient Management Practices (PNMPs) are quantified using internationally recognised agronomic indicators as shown in Table 6:

These metrics rely on yield and fertiliser application records, making them feasible for widespread implementation at the farmer level. Soil health analyses are conducted in parallel to verify sufficiency of phosphorus (P), potassium (K) and micronutrients, ensuring that N management improvements do not compromise overall soil fertility.

7.7.2 Emission quantification

To generate globally credible evidence of NH_3 and GHG mitigation, UPCAMP incorporates direct emission measurements a shown in Figure 9:

The integration of field-level agronomic metrics with high resolution emission monitoring, supported through PM-PRANAM funding, establishes a technical framework for validated emission reduction credits. This not only quantifies the environmental co-benefits of fertiliser efficiency but also positions as a global leader in linking fiscal policy reforms to measurable air quality and climate outcomes. The MRV system lays the groundwork for future climate finance mechanisms, enabling reliable investment in sustainable agricultural interventions worldwide.

7.8 Technological interventions: “Neem Plus”, Urea deep placement and 4R stewardship

The most effective pathway to mitigate NH_3 emissions, improve NUE and reduce fiscal pressures is through the adoption of precision nutrient management practices (PNMPs), grounded in the globally recognised 4R nutrient stewardship framework (FAO, 2023; Ramalingappa et al., 2023).

The application of the 4R principles is outlined in Figure 10:

These principles are specifically designed to minimise nutrient losses, including volatilisation of NH_3, leaching and runoff, thereby reducing the formation of secondary $PM_{2.5}$ and greenhouse gas emissions.

Beyond the 4R framework, specific technological interventions are critical for reducing the atmospheric nitrogen load:

- **The “Neem Plus” strategy**

While India’s mandatory “Neem Coated Urea” policy was a first step, research indicates it is insufficient for substantial ammonia abatement. The “Neem Plus” proposal advocates for coating urea with urease inhibitors (such as NBPT).

- Studies show that urease inhibitors can reduce ammonia volatilisation by approximately 70% compared to conventional urea.
- Mandating “Neem Plus” (neem + urease inhibitor) by 2030 is projected to offer an additional 5% nitrogen saving over neem-coated urea alone.

- **Urea deep placement (UDP) technology**

UDP involves the sub-surface application of large urea granules (often “super granules”) directly into the root zone.

- By placing the nitrogen source below the soil surface, UDP significantly limits the exposure of urea to the air and surface enzymes, thereby drastically reducing NH3 volatilisation compared to traditional surface broadcasting.
- This technology ensures that nutrients are available precisely where the crop needs them, supporting higher yields with lower total nitrogen application.

- **Slow-release and controlled-release formulations**

Transitioning from conventional urea to slow-release fertilisers (SRFs) or enhanced efficiency fertilisers (EEFs) is a critical long-term strategy.

TABLE 6 METRICS FOR QUANTIFYING PRECISION NUTRIENT MANAGEMENT PRACTICES (PNMPS)

Metric	Definition	Purpose
Partial factor productivity (PFP)	Crop yield divided by N applied	Measures overall efficiency of N use in producing yield
Crop NUE	Yield under fertiliser application divided by N applied	Tracks crop-specific nitrogen uptake efficiency
Agronomic efficiency (AE)	Incremental yield per unit N applied	Evaluates the productivity benefit of applied N

FIGURE 9 FRAMEWORK FOR DIRECT QUANTIFICATION OF NH_3 AND GHG EMISSIONS

Technology deployment	High-resolution monitoring	Integrated data modeling
Cost-effective, user-friendly handheld detectors are placed at KVK (Krishi Vigyan Kendra) level to routinely measure NH_3 concentrations in the field.	Closed-chamber techniques are employed at 18 representative locations to capture NH_3 fluxes and GHG emissions (N_2O, CH_4) during critical periods, such as fertiliser application and key crop growth stages. Large instruments, including LICOR gas analyzers, are specifically allocated in the project budget for precise measurements.	Agronomic and emission data are combined and modeled using biogeochemical models (e.g., DNDC) to estimate overall reductions in N losses and GHG emissions attributable to PNMP adoption.

- These fertilisers use biodegradable coatings or chemical modifications to release nitrogen at a pace that matches the crop’s physiological demand.
- By preventing a “spike” in nitrogen availability, these formulations minimise the surplus nitrogen that would otherwise escape as NH3 or leach into groundwater.

This includes transitioning towards biodegradable coatings and using biologically synthesised urea-based nanomaterials which have shown promise in reducing bulk urea usage by 25% without yield penalties.

7.9 The economic rationale for cost-effectiveness of ammonia control

Closing the policy gaps requires demonstrating that ammonia control is not just an environmental cost but an economic investment.

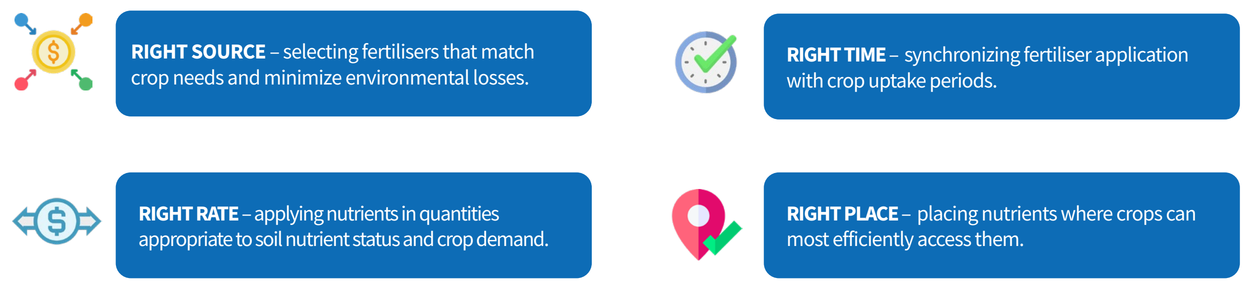
- Research by Gu et al. (2021) demonstrates that abating ammonia emissions is a more cost-effective strategy for mitigating $PM_{2.5}$ than further tightening controls on NOx and sulphur dioxide SO2.
- The lower-bound savings potential for ammonia control in winter is estimated at 8,000 per ton of NH3, making it a “low-hanging fruit” for air quality improvement compared to expensive industrial scrubbers (Pinder et al., 2007).
- Globally, trade-related agricultural ammonia emissions are responsible for 61,000 premature deaths annually. Mitigating these emissions yields societal health benefits that vastly outweigh the implementation costs of technologies like urease inhibitors (Ma et al., 2021).

7.10 A rural air quality network: Closing the monitoring gap

To address the monitoring deficit, the infrastructure for air quality measurement must be decoupled from its exclusive focus on the urban environment to ensure the inclusion of rural agricultural source zones.

- Expanding the Central Pollution Control Board’s (CPCB) network to include “rural background stations” is essential to separate local urban pollution from regional agricultural transport (CSE, 2024).
- Utilising satellite data (e.g., from AIRS and MODIS sensors) can help identify ammonia hotspots in the western and eastern IGP that are currently missed by ground monitors, allowing for targeted intervention in “high emission” districts (Beale et al., 2022).

FIGURE 10 APPLICATION STRATEGIES FOR THE 4R PRINCIPLES OF PRECISION NUTRIENT MANAGEMENT



7.11 Mitigating systemic economic risk

India's heavy reliance on imported fertilisers accounting for around 18% of the subsidised annual consumption exposes national budgets to global commodity price volatility (Das, 2025). PM-PRANAM addresses this risk by promoting domestic production and the adoption of alternative, high-efficiency fertilisers through the 70% allocation towards asset creation. This approach enhances self-reliance, stabilises agricultural input costs, and ensures long-term resilience of the sector against external shocks.

7.12 Integrated Benefits Summary

India's transition towardss balanced nutrient management and enhanced efficiency fertilisers generate a wide spectrum of co-benefits that extend beyond air quality improvements. The multifaceted benefits of this approach are summarised in Table 7.

7.13 Multi sectoral and fiscal impacts

This integrated approach ensures that environmental, health and economic benefits are achieved concurrently, demonstrating that fiscal reform in fertiliser policy can serve as a cornerstone of air and climate strategy. The projected impacts span air quality improvement, climate benefits, enhanced farmer economics, fiscal sustainability and broader environmental co-benefits are shown in Table 8.

TABLE 7 SUMMARY OF INTEGRATED CO-BENEFITS FROM BALANCED NUTRIENT MANAGEMENT AND POLICY INTERVENTIONS

Dimension	Impact	Mechanism
Air quality	Reduced NH_3 emissions → Lower secondary $PM_{2.5}$	PNMP adoption + EEFs (NCU, NU)
Climate	Lower N_2O emissions → GHG mitigation	Improved NUE, reduced nitrogen loss
Farmer economics	Reduced input costs, increased net returns	Use of EEFs, financial incentives under PM-PRANAM
Fiscal	Sustained subsidy savings → Reduced central expenditure	50% grant to states + 50% retained as central savings
Food security & productivity	Maintains or improves yields	Right Rate, Right Source, Right Time, Right Place (4R) framework
Systemic resilience	Reduced import dependency, stable input prices	Investment in domestic fertiliser production and alternative technologies

TABLE 8 PROJECTED MULTI-SECTORAL AND FISCAL IMPACTS OF INTEGRATED FERTILISER POLICY REFORMS

Aspect	Projected Impact	Mechanism
Air quality	25–30% reduction in chemical urea → 27–41% reduction in NH_3 emissions → measurable $PM_{2.5}$ decrease	PNMP adoption + EEFs (NCU, NU)
Climate	Reduced N_2O emissions → lower GHG forcing	Enhanced NUE and reduced N losses
Farmer economics	Lower input costs, higher profitability	Financial incentives, precision application
Fiscal sustainability	Shared subsidy savings reduce central fiscal burden	PM-PRANAM grant feedback loop (50% of savings to states)
Environmental co-benefits	Improved soil health, water quality, biodiversity conservation	Balanced NPK application, reduction in runoff and leaching

CHAPTER VIII

Policy recommendations

Addressing the rising burden of ammonia emissions and secondary $PM_{2.5}$ formation across the IGP-HF region requires a comprehensive and integrated policy approach. The recommendations outlined below provide a coherent roadmap for coordinated short-term and long-term interventions to reform fertiliser governance, enhance cross-border and inter-state cooperation, strengthen monitoring frameworks, and advance sustainable nitrogen management. Short-term actions should prioritise reducing current emission levels, while long-term structural reforms must institutionalise improved "packages of practices" (PoP) through sustained capacity building and governance improvements across the region.

A. Short-term interventions (0–3 years)

i. Mandate a national "Neem Plus" fertiliser standard

While neem-coated urea (NCU) has delivered important improvements in nitrate retention, it has not substantially reduced ammonia volatilisation, a critical gap given alkaline soils and warm climatic conditions. As studies show, the addition of urease inhibitors such as NBPT can reduce NH_3 losses by nearly 70% during surface application. A national transition from NCU to "Neem plus urea" comprising neem coating plus an approved urease inhibitor would represent a technically feasible and cost-effective leap in improving nitrogen use efficiency (NUE), reducing air pollution, and lowering fertiliser wastage.

Implementation would require a phased mandate, beginning with high emission districts in the Indian states of Uttar Pradesh, Punjab, Bihar, and the Nepal Terai region, followed by state-wide and national adoption by 2030. Fertiliser manufacturers must be supported through technology transfer and production incentive frameworks. This policy must be integrated with the existing subsidy architecture to ensure affordability, thereby preventing farmers from shifting back to conventional urea. Embedding inhibitor technology within the subsidy system itself, can internalise environmental benefits without placing behavioural burdens on farmers.

ii Nano urea technologies available in India should be evaluated in multiple agro-climatic zones (ACZs) of India in long-term field trials and based on the outcomes, those should be promoted for achieving food security while 25% replacement of conventional urea from certain crops and ACZs. State agriculture universities may develop and provide package of practice for usage of nano fertiliser in specific crop types and ACZs.

iii. Slurry from bio-gas plants needs to be injected as biofertilisers - a valuable, nutrient-rich byproduct of anaerobic digestion that is ideal for soil injection - acting as a potent organic fertiliser to boost crop yields and improve soil health through enhanced fertility and moisture retention. Its widespread adoption reduces reliance on synthetic chemical fertilisers and mitigates air pollution by preventing the ammonia volatilisation associated with surface broadcasting. While highly beneficial for sustainable nitrogen management, careful application protocols are required to maximise nutrient-use efficiency and avoid localised negative environmental effects.

2. Strengthen NCAP by incorporating ammonia-reduction targets

Current frameworks, such as India's National Clean Air Programme (NCAP) and Nepal's Clean Air Quality Management (CAQM) and other pollution control strategies, lack a structured approach to regulating agricultural ammonia. Given that ammonia is a dominant precursor for secondary $PM_{2.5}$, especially during winter inversions common to the entire IGP, mitigation frameworks must evolve from urban-centric dust control to chemically informed strategies.

A reformed regional approach should:

- Establish district-wise NH_3 reduction targets, particularly for the transboundary agricultural belt.
- Require non-attainment cities (e.g., Lahore, Delhi, Kathmandu, Dhaka) to coordinate pollution reduction strategies with their agricultural hinterlands.
- Integrate agricultural extension agencies and Krishi Vigyan Kendras (KVKs) into Clean Air Action Plans (CAAP).
- Allocate funding specifically for precursor mitigation rather than solely for visible urban pollutants.

3. Establish a rural air quality monitoring network

IGP-HF air-monitoring infrastructure is overwhelmingly urban-biased, with only a small number of stations located in agricultural regions. As a result, rural ammonia emissions remain poorly quantified, despite being a dominant source of secondary $PM_{2.5}$. For expanding programs like PM-PRANAM to reach farmers across the IGP-HF and promoting the adoption of enhanced-efficiency fertilisers (Neem Plus, nano-urea) and sustainable farm management practices, strengthening of rural monitoring is essential. This would support the designing of targeted interventions, validating PM-PRANAM outcomes, and enabling regional airshed governance.

A national rural monitoring network should involve:

- Deployment of low-cost NH_3 sensors in high use fertiliser districts.
- Calibration with advanced instruments (LICOR, closed-chamber flux systems).
- Integration with satellite NH_3 measurements (AIRS, MODIS).
- Public dashboards linking agricultural seasons with ammonia trends.

This system would allow policymakers to monitor real-time emissions and adjust regulatory and subsidy measures accordingly.

4. Create a National Nitrogen Authority (NNA) for integrated governance

The country currently lacks a unified institutional mechanism to coordinate nitrogen management across production, pricing, soil health, food security, and air quality. Fertiliser pricing policy, agricultural practices, and air pollution control operate in silos that often send conflicting signals. To address this, a National Nitrogen Authority (NNA) should be established to coordinate inter-ministerial policies and align the nitrogen cycle within a single governance framework. To effectively manage the diverse needs of the IGP-HF, the NNA should be structured with dedicated state-level arms to address the specific nitrogen requirements of different states, which vary significantly due to differences in soil health, crop types, and ACZs. Key responsibilities of this authority would include:

- Setting national nitrogen budgets and NH_3 reduction pathways.
- Coordinating PM-PRANAM, soil-health initiatives, and NCAP reforms.
- Guiding research on enhanced efficiency fertilisers and nitrogen technologies.
- Developing annual nitrogen accounts at state and district levels to ensure interventions match zonal requirements.

Such a body would mirror institutions in Europe and East Asia that have successfully reduced nitrogen losses across agriculture, water, and air systems.

5. Establish nitrogen budgets and state-level nitrogen ceilings

Nitrogen budgets are essential tools for quantifying nitrogen entry (fertilisers, manure, atmospheric deposition) and exit (crop uptake, volatilisation, leaching). The absence of district-level nitrogen budgets in IGP countries limits the capacity to monitor surplus nitrogen the primary driver of ammonia emissions.

The government should mandate state and district nitrogen budgets for all major agricultural regions, beginning with the IGP-HF. These budgets would enable:

- Target-setting for nitrogen reduction.
- Prioritisation of high-surplus districts.
- Integration of soil-health card data and fertiliser sales records.
- Evidence-based subsidy reform.

Nitrogen ceilings, like those used in the EU, can be phased in as budgets mature, beginning with the nitrogen-intensive zones of the cultivated north-western IGP.

6. Accelerate regional fertiliser-efficiency incentives and integrate with clean air planning

While specific programs like India's PM-PRANAM have demonstrated strong early potential to reduce chemical fertiliser use and promote sustainable alternatives, achieving regional air quality goals requires rephrasing these incentives as a broader IGP-HF strategy. The impact on air quality across the region will depend on integrating these fiscal incentives with national clean air programs, localised extension networks, and standardised Monitoring, Reporting, and Verification (MRV) systems.

Jurisdictions across the IGP-HF should adopt "fertiliser-saving" incentives as a core strategy within their regional and city-level clean air action plans. Opportunities for regional integration include:

- **Linking fiscal incentives to technology adoption**: Scaling incentives for the use of enhanced-efficiency fertilisers (EEFs), such as "Neem Plus" (urease inhibitors) nano-urea, deep placement of urea super granules (USGs), nitrogen fixing biofertilisers or compressed biogas (CBG) based soil enhancers to reduce the atmospheric ammonia pool.
- **Funding rural monitoring infrastructure**: Utilising agricultural reform funds to establish rural air quality monitoring stations in high-fertiliser-use districts to capture ammonia hotspots currently missed by urban-centric networks.
- **Aligning agricultural targets with air quality goals**: Synchronising district-level fertiliser reduction targets with the clean air action plans of downwind "non-attainment" cities to address the rural-urban pollution continuum.
- **Re-aligning subsidies for performance-based farmer payments**: Implementing "green benefit transfers" like the models piloted in Andhra Pradesh or proposed in China's Nitrogen Credit System where cash payments are conditioned on validated nitrogen reductions at the farm level.
- **Institutionalising multi-sectoral interventions**: Transitioning from fragmented departmental silos to an integrated approach that treats fertiliser efficiency as both a food security necessity and a primary air-quality intervention.

By adopting these integrated strategies, the nations of the IGP-HF can move towards the "35-by-35" target, ensuring that fiscal reforms in the agricultural sector serve as a cornerstone of the regional clean air strategy.

7. Boost the role of Krishi Sakhis and farmer-field school systems

Behavioural change in the IGP requires accessible, localised knowledge. Leveraging India's *Krishi Sakhi* program and Nepal's *Junior Technical Assistant* (JTA) networks can bridge the gap between policy and practice. Coupling these human networks with farmer field schools (FFS) would enable hands-on demonstration of deep placement, banding, urease inhibitors, and precision nutrient tools.

A coordinated extension push could:

- Promote Neem Plus usage alongside other "low hanging" technologies such as urea deep placement, banding, and the use of leaf colour charts.
- Assist with soil-sample collection.
- Provide crop-stage fertiliser advisories.
- Act as the "human sensor network" for monitoring policy compliance.

This decentralised extension model is essential for reaching millions of smallholders in the IGP-HF.

8. Integrate green ammonia into regional fertiliser supply chain

Transitioning to green ammonia offers a dual benefit by decarbonising urea production and reducing lifecycle emissions. While green ammonia production may be concentrated in specific hubs (e.g., coastal India or hydropower-rich Nepal), its integration into the fertiliser supply chain should remain a regional priority. A voluntary Green Ammonia Procurement Obligation (GAPO) could encourage manufacturers across the IGP to incorporate low-carbon ammonia, aligning agricultural reform with the region's climate commitments.

9. Mainstream FUE in regional science policy finance dialogues and platforms

Ammonia acts as a regional, transboundary pollutant that ignores administrative borders, making the IGP-HF one of the most chemically reactive airsheds globally. However, establishing a standalone cooperation framework solely for fertiliser use efficiency (FUE) is not practically viable. Instead, FUE must be mainstreamed into existing regional science-policy-finance dialogues and platforms.

The primary vehicle for this coordination is the regional science-policy-finance dialogue (SPFD), a platform co-convened by ICIMOD and the World Bank to drive collective action in the IGP-HF. This voluntary platform facilitates cooperation between scientists, policymakers, and financial institutions across Bangladesh, India, Nepal, and Pakistan to address shared environmental risks. By embedding FUE into the SPFD and related regional dialogues, the region can coordinate:

i. Aligning NH3 reduction goals within broader regional air quality frameworks to lower the "ammonia ceiling" that sustains high $PM_{2.5}$ levels.

ii. Developing consistent regional standards for enhanced-efficiency fertilisers like "Neem Plus" (NBPT inhibitors) and nano-urea.

iii. Utilising the platform to share meteorological data, satellite ammonia measurements, and source apportionment models to identify transboundary hotspots.

iv. Aligning Monitoring, Reporting, and Verification (MRV) protocols to ensure that state-level nitrogen reductions are scientifically validated and transparent.

v. Leveraging regional finance dialogues to support the scaling of "green benefit transfers" and funding for rural monitoring networks that ground-truth ammonia emissions.

This mainstreamed approach is essential for operationalising the "Thimphu Outcome", the regional agreement to pursue the "35-by-35" aspirational goal of reducing annual $PM_{2.5}$ to 35 ug/m3 by 2035 from a current population-weighted regional baseline of approximately 75-100 μg/m^3 (HEI, 2024). Coordinated action through these platforms is estimated to be 45% more cost-effective than isolated national measures in meeting clean-air targets (World Bank, 2022).

B. Long-term interventions (3–7 Years)

The goal is to move from "emergency fixes" to a permanent system where farmers efficiently manage nitrogen as a standard practice. This phase focuses on institutionalising the successful pilots into region-wide structural reforms.

1. Decouple productivity from nitrogen consumption (the strategic goal)

Historical trends in the IGP-HF show that higher yields are currently driven by higher fertiliser input. This coupling must be broken to ensure sustainable growth.

The region should adopt a strategic goal like China's "zero growth" policy, where agricultural productivity continues to rise while total nitrogen consumption is capped and eventually reduced. This requires shifting the performance metrics of agricultural departments from "Fertiliser Sales" to "Nitrogen Use Efficiency (NUE)."

2. Make the "package of practices" (PoP) the new standard

Standardize the Rules and adopt the 4R Rule (Right Source, Right Rate, Right Time, Right Place) as the mandatory standard for fertiliser use.

Shift farmers to adaptive nutrient management, where fertiliser amounts are adjusted every season based on actual soil test results and crop yields, rather than using a fixed, habit-based amount.

3. Regional capacity building: training and incentivising farmers

To achieve widespread behavioural change, the extension system must utilise locally relevant frameworks across all IGP-HF countries:

- **Farmer field schools (FFS)**: Establish and scale FFS networks across the region where farmers can observe the benefits of precision nutrient management on localised demonstration plots.
- **Localised extension networks**:

  India: Leverage Krishi Sakhis (women extension workers) and Krishi Vigyan Kendra's (KVKs) as the primary hubs for technical advice and localized soil testing.

  Nepal: Utilise the network of Junior Technical Assistants (JTAs) and Junior Technicians (JTs), who provide on-site technical support and door-to-door farmer visits for nutrient management.

  Pakistan and Bangladesh: Mobilize Agricultural Extension Officers (AEOs) and Sub-Assistant Agriculture Officers (SAAOs) to lead sub-district level training on the 4R framework and tools like Leaf Color Charts.
- **Direct financial incentives**: Utilise fiscal mechanisms like PM-PRANAM (India) or equivalent regional agricultural subsidy reforms to provide direct "green benefit transfers". For example, providing direct payments such as ₹5,000 per hectare to farmers who successfully adopt low-emission practices helps bridge the "incentive gap" and reduces the perceived risk of transitioning from traditional urea application.

4. Governance structure and regional platforms Rather than isolated national structures, the region must integrate into broader platforms:

- **National Nitrogen Authority (NNA)**: Each nation should establish an NNA to coordinate policies across Agriculture, Environment, and Fertiliser ministries, ensuring that food security goals do not conflict with air quality mandates.
- **Science-policy-finance dialogue (SPFD)**: Mainstream FUE into the SPFD, a platform co-convened by ICIMOD and the World Bank. This platform serves as a voluntary mechanism for Bangladesh, India, Nepal, and Pakistan to synchronise ammonia reduction targets and share transboundary meteorological data.

5. Verify the results

Implement a region-wide Monitoring, Reporting, and Verification (MRV) system that is scientifically and financially linked.

- **Air quality linkage**: This system must link farm-level data (actual nitrogen saved) with atmospheric emission monitoring (ammonia hotspots detected via satellite or rural monitors) to provide valid proof of air quality improvements.
- **"35-by-35" alignment**: Use verified reductions to track progress towards the aspirational "35-by-35" target the regional goal to reduce annual $PM_{2.5}$ to 35 ug/m3 by 2035, as endorsed in the Thimphu Outcome.

CHAPTER IX

Conclusions

Agricultural NH_3 emissions have emerged as a major, yet unregulated, driver of $PM_{2.5}$ pollution across the IGP-HF region. While countries such as India, Pakistan, Nepal, and Bangladesh have focused on controlling urban emission sources, the chemical precursors generated by inefficient fertiliser use remain largely unaddressed. This policy gap not only sustains persistent winter smog across the IGP-HF airshed but also results in significant economic losses through wasted subsidies and declining soil health.

India's PM-PRANAM scheme offers a scalable blueprint for the region, shifting the focus from consumption to conservation. When combined with technical solutions like "Neem Plus" urea and lessons from global best practices, it demonstrates that reducing ammonia emissions is both economically rational and vital for agricultural sustainability. However, fragmented city-level interventions are no longer sufficient. Given that the IGP-HF region functions as a single atmospheric basin, durable air quality improvements require an Indo-Gangetic Airshed Cooperation Mechanism to harmonise fertiliser standards and align nitrogen policies across borders.

Sustainable nitrogen management offers a triple dividend: reduced fiscal burdens, restored soil fertility, and improved public health. By adopting the reforms outlined in this report, including region-specific nitrogen budgets, coordinated airshed governance, and improved agricultural extension networks, the IGP-HF countries can move decisively towardss achieving the "35-by-35" clean air target, safeguarding the health and productivity of the 500 million people who inhabit this critical landscape.

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